NASA Technical Memorandum

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Shuttle Coherent Atmospheric Lidar Experiment

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National Aeronautics and
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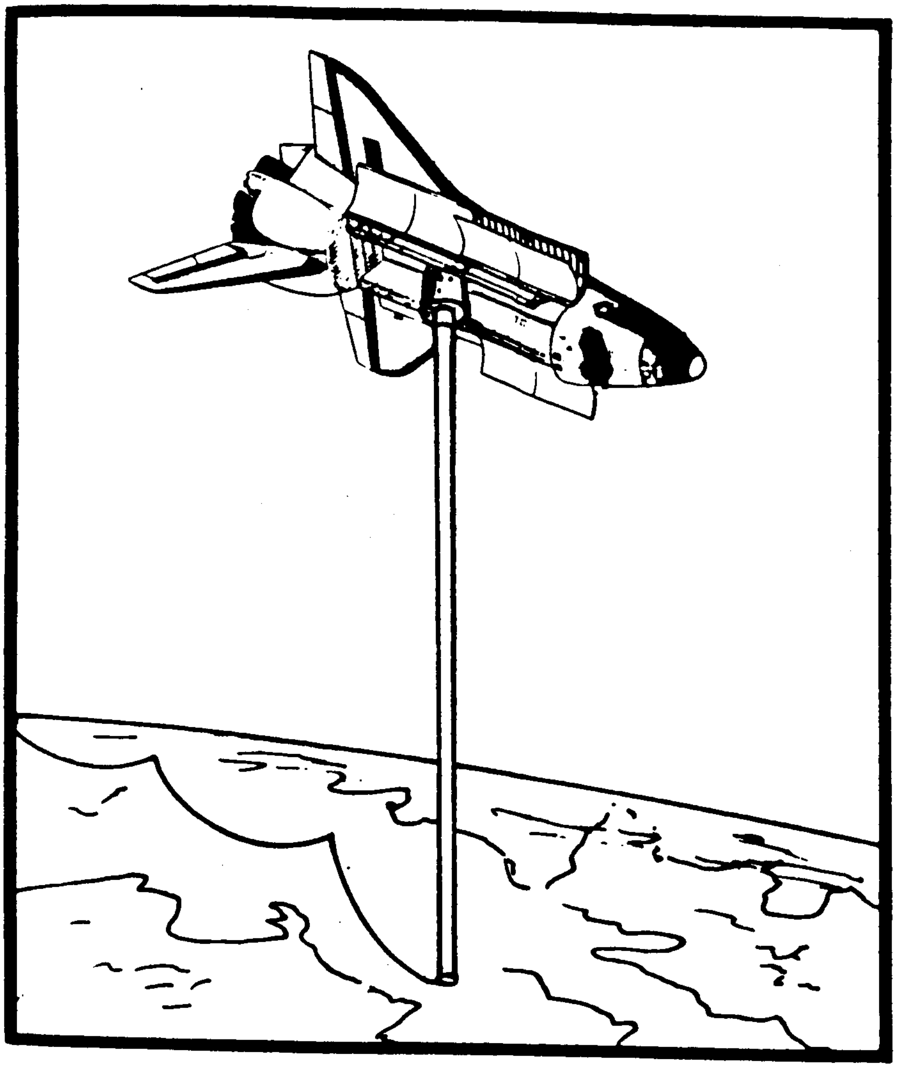
George C. Marshall Space Flight Center

Shuttle Coherent Atmospheric Lidar Experiment (SCALE)



Prepared by
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SPECTRA TECHNOLOGIES, INC	– LASER STUDY
KORSCH OPTICS	– TELESCOPE DESIGN
SIMPSON WEATHER ASSOCIATES	– SIMULATION STUDIES
JOHNSON SPACE FLIGHT CENTER	– ORBITAL MANEUVERING SIMULATION

SCALE

INTRODUCTION

SCALE

WHY MEASURE WINDS FROM SPACE?

THERE IS STRONG SUPPORT FROM THE SCIENCE COMMUNITY FOR GLOBAL WIND MEASUREMENT. IT HAS BEEN GIVEN HIGH PRIORITY BY:

- NATIONAL WEATHER SERVICE
- AIR WEATHER SERVICE
- EARTH SYSTEM SCIENCE COMMITTEE
- EARTH OBSERVING SYSTEM REPORT
- OSSA GLOBAL SCALE ATMOSPHERIC RESEARCH PANEL INSTRUMENT DEVELOPMENT PANEL
- NASA OSSA GLOBAL WIND MEASUREMENT SYMPOSIUM & WORKSHOP
- GLOBAL CIRCULATION MODELERS
- NATIONAL ACADEMY OF SCIENCE

SCALE

WHY CO_2 LASERS FOR COHERENT LIDAR WIND MEASUREMENT?

- THEY ARE THE <u>ONLY</u> LASERS CURRENTLY AVAILABLE THAT HAVE SUFFICIENT POWER AND HIGH ENOUGH EFFICIENCY FOR A SPACE BASED COHERENT LIDAR
- THERE ARE <u>NO</u> SOLID STATE LASERS IN EXISTENCE WHICH WILL PERFORM THE DESIRED TASK
  - DIODE ARRAYS MUST STILL BE DEVELOPED TO OBTAIN NECESSARY EFFICIENCIES
  - CANDIDATE MATERIALS FOR $\lambda > 1.7 \mu m$ ARE STILL BEING SOUGHT
- CO_2 LASERS CAN BE SPACE QUALIFIED
  - CO_2 LIDAR TECHNOLOGY IS THE ONLY PROVEN TECHNOLOGY FOR SPACE–BASED TROPOSPHERIC WIND MEASUREMENTS
  - CO_2 LIDAR TECHNOLOGY CAN PROVIDE LASER RANGING AND DIAL CAPABILITIES FOR MEASUREMENT OF H_2O, NH_3, O_3, AND CO.
  - OTHER LASER TECHNOLOGIES HAVE DEMONSTRATED CAPABILITIES FOR DIAL AND RANGING, BUT OPERATION OF SUCH SYSTEMS PROVIDES NO DIRECT BENEFIT TOWARD GLOBAL WIND MEASUREMENT

MSFC COHERENT LIDAR RESEARCH AND DEVELOPMENT HISTORY

1967: FIRST MEASUREMENT OF ATMOSPHERIC WINDS USING COHERENT DOPPLER LIDAR

1968: FIRST MEASUREMENT OF AIRCRAFT WAKE VORTICES USING COHERENT DOPPLER LIDAR

1972: FIRST FLIGHT OF AN AIRBORNE PULSED COHERENT DOPPLER LIDAR FOR CLEAR AIR TURBULENCE MEASUREMENT

1974: FIRST MEASUREMENT OF 3-D WINDS EMPLOYING A VAD SCAN TECHNIQUE WITH A CW COHERENT DOPPLER LIDAR

1974: DEVELOPED FIRST SYSTEM FOR DETECTING AND TRACKING AIRCRAFT WAKE VORTICES WITH COHERENT DOPPLER LIDAR

1974: FIRST MEASUREMENT OF HIGH STACK EMISSION FLOW RATE FOR POLLUTION MONITORING WITH COHERENT DOPPLER LIDAR

1975: FIRST BI-DIRECTIONAL VELOCITY PROFILE MEASUREMENT OF DUST DEVILS USING COHERENT DOPPLER LIDAR

1977: FIRST SIMULTANEOUS MEASUREMENT OF RADIAL AND TRANSVERSE WIND COMPONENTS USING COHERENT DOPPLER LIDAR

1978: FIRST GROUND BASED MEASUREMENT OF THUNDERSTORM OUTFLOW AND ASSOCIATED WIND SHEAR WITH A PULSED COHERENT LIDAR

1981: FIRST FLIGHT OF AIRBORNE PULSED COHERENT DOPPLER LIDAR FOR WINDFIELD MAPPING

1981: FIRST FLIGHT OF AN AIRBORNE CW COHERENT LIDAR FOR ATMOSPHERIC BACKSCATTER MEASUREMENT

1981: DEVELOPED FIRST PLAN FOR SYSTEMATIC DETERMINATION OF ATMOSPHERIC BACKSCATTER COEFFICIENTS

1982: FEASIBILITY STUDY FOR COHERENT DOPPLER LIDAR FREE–FLYER FOR GLOBAL WIND MEASUREMENT

1982: FIRST ATMOSPHERIC BACKSCATTER MODEL DEVELOPMENT FROM SAGE AND SAM II DATA

1983: FIRST DUAL DOPPLER LIDAR MEASUREMENTS OF ATMOSPHERIC WINDS

1984: FIRST HETERODYNE MEASUREMENTS OF WINDS USING AN ISOTOPIC LASER

1985: FIRST FEASIBILITY STUDY FOR SPACE QUALIFICATION OF A CO_2 LASER FOR GLOBAL WIND MEASUREMENT

1985: FEASIBILITY STUDY FOR SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

1985: DEVELOPED DETAILED PLAN FOR GLOBAL ATMOSPHERIC BACKSCATTER ASSESSMENT

1985: DEVELOPED AIRBORNE DOPPLER LIDAR FOR ATMOSPHERIC BACKSCATTER MEASUREMENT AT ISOTOPIC WAVELENGTHS

SCALE

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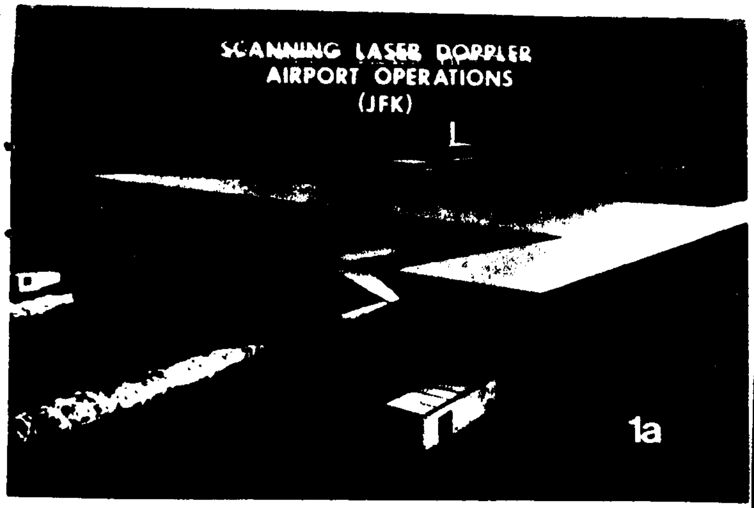

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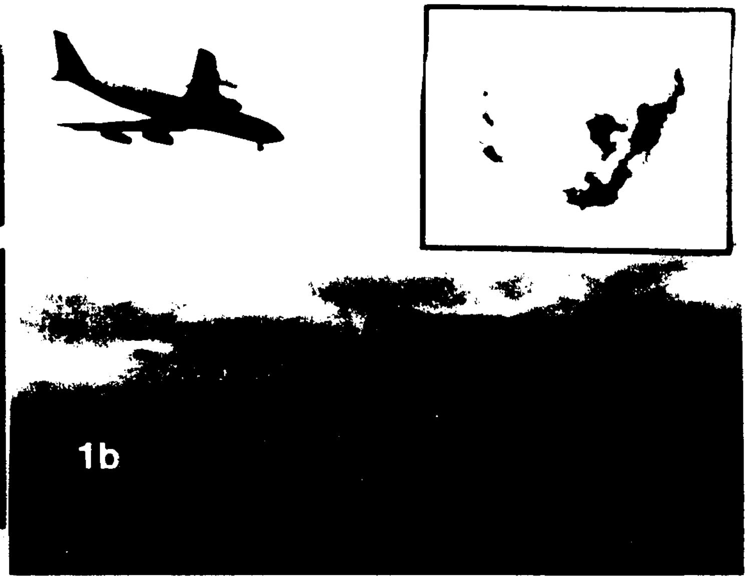

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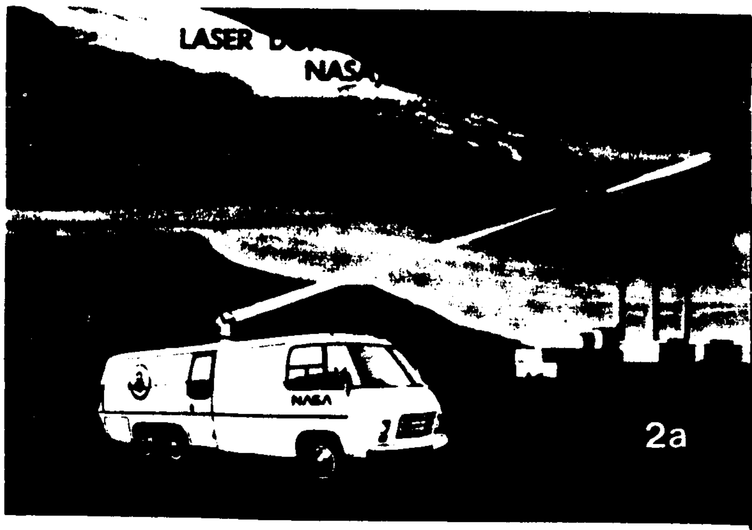

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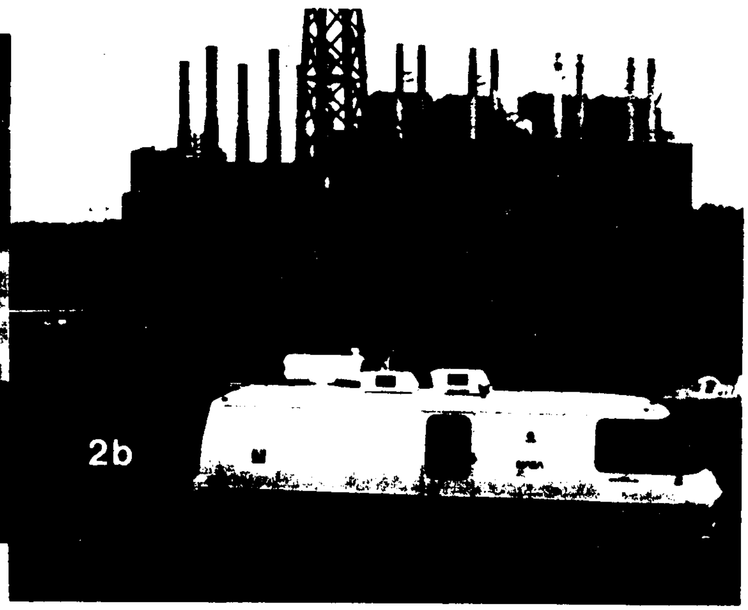

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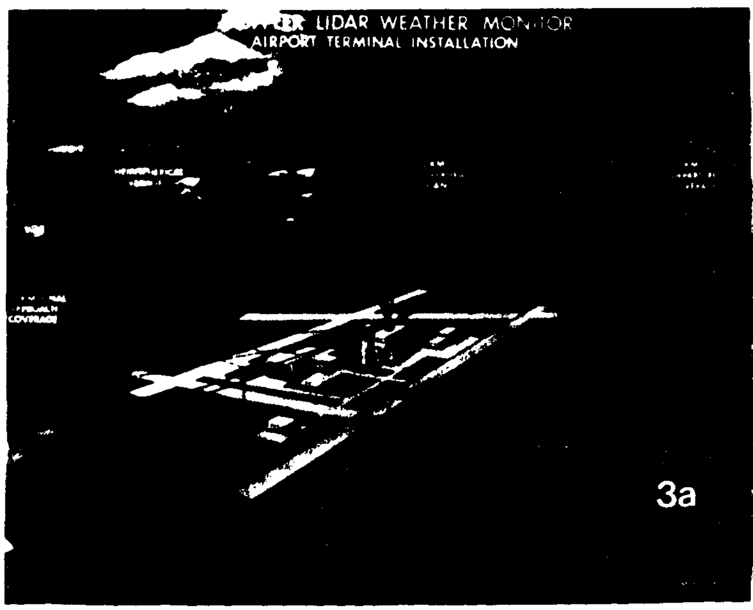

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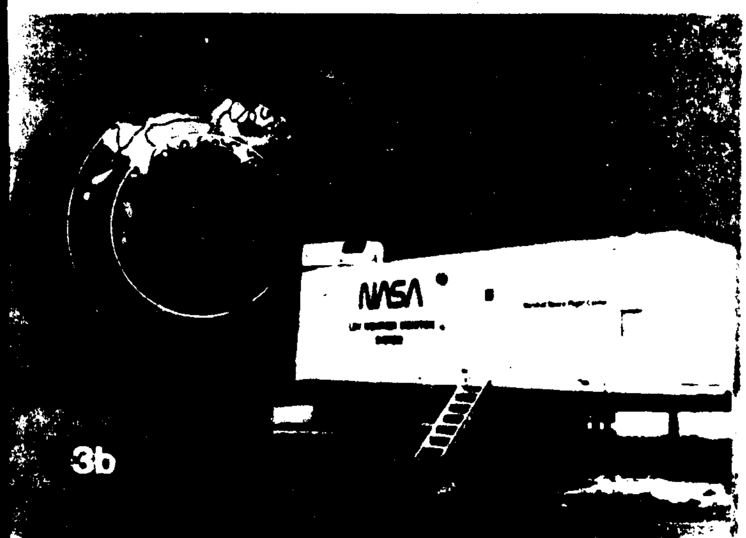

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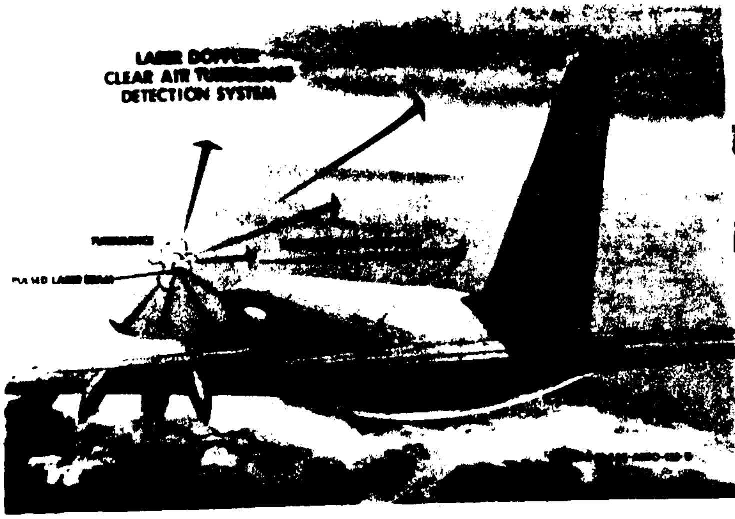
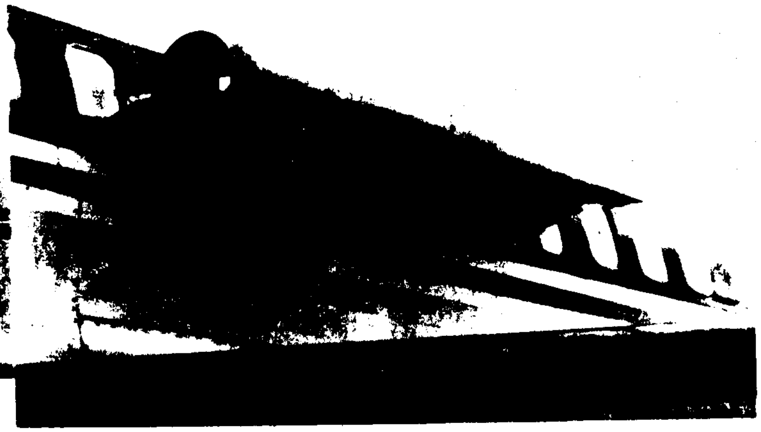
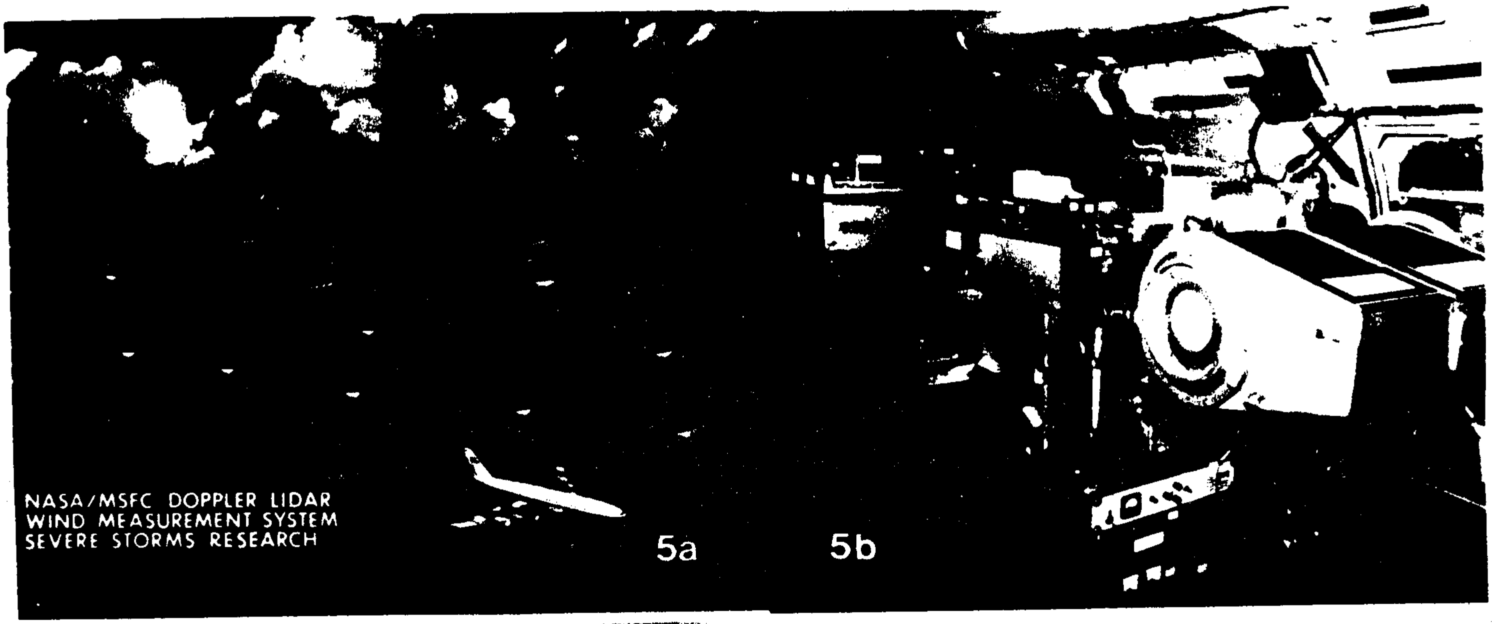


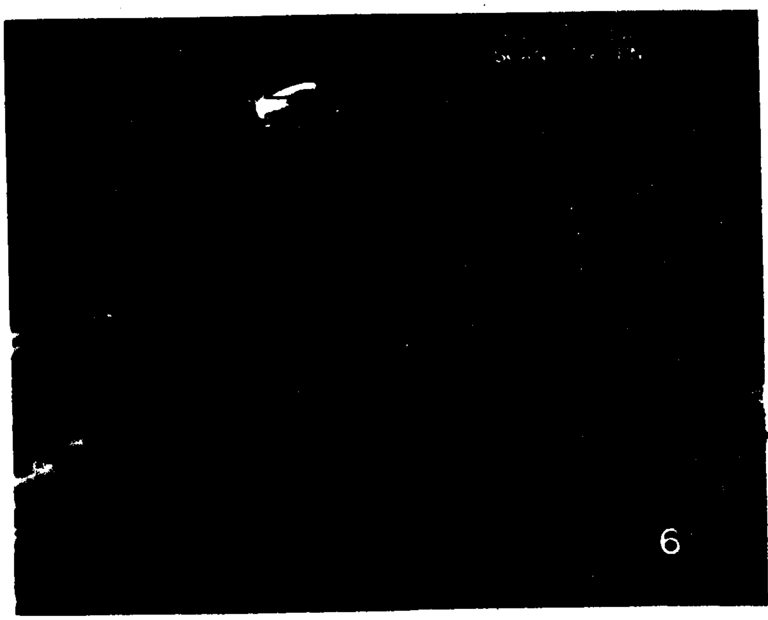




NASA/MSFC DOPPLER LIDAR
WIND MEASUREMENT SYSTEM
SEVERE STORMS RESEARCH

5a

5b



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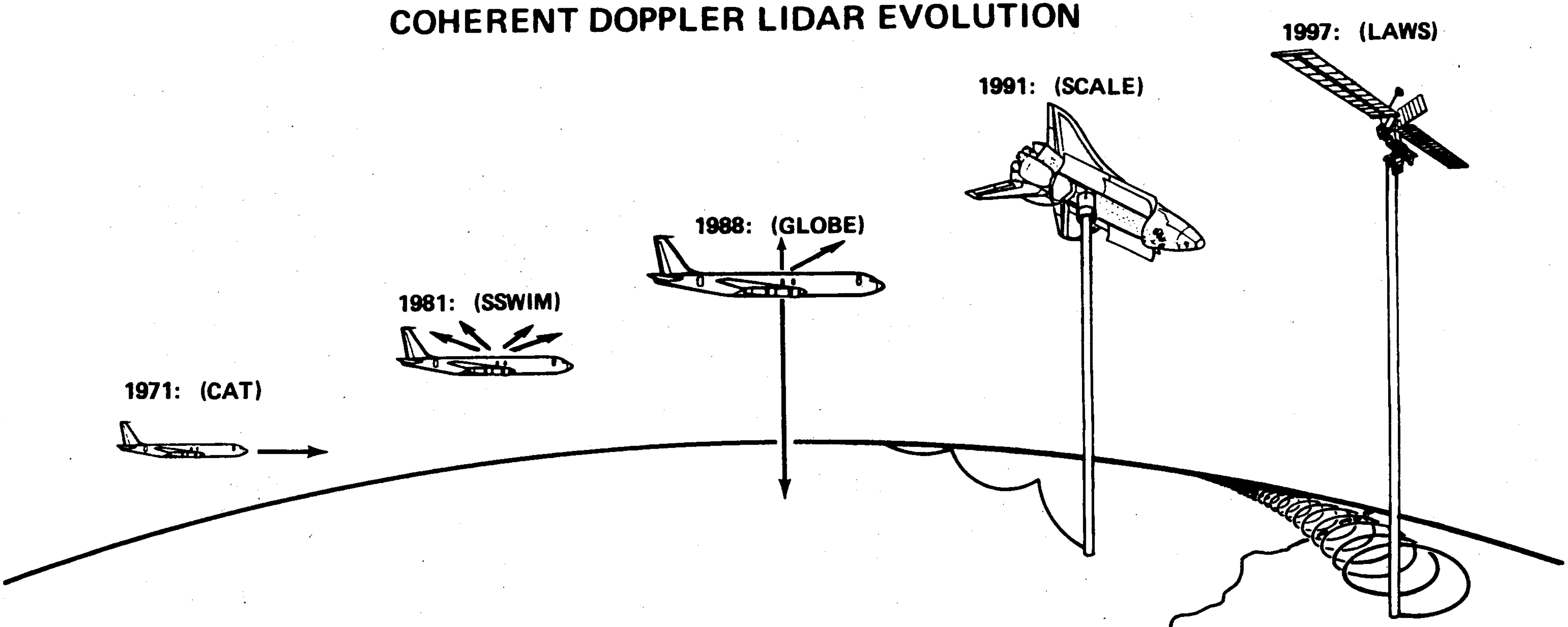
SCALE

CURRENT EFFORTS TOWARD ESTABLISHING THE FEASIBILITY OF A SPACEBORNE DOPPLER LIDAR FOR GLOBAL WIND MEASUREMENT

o SIMULATION STUDIES TO DETERMINE BENEFIT OF GLOBAL WIND DATA TO THE GCM	– GSFC
o SIMULATION STUDIES TO ASSESS IMPACT OF SCANNING AND SAMPLING STRATEGIES ON MESOSCALE MEASUREMENTS FROM SPACE	– SIMPSON WEATHER ASSOCIATES – MSFC
o DERIVATION OF CO_2 BACKSCATTER FROM SAGE AND SAM II DATA	– IFAORS (MSFC AND LRC)
o AEROSOL SCATTERING PHYSICS	– PENN STATE (MSFC)
o AIRBORNE CO_2 BACKSCATTER/AEROSOL MEASUREMENTS	– MSFC, ARC
o GROUND BASED CO_2 BACKSCATTER MEASUREMENTS	– AFGL, JPL, LRC, MSFC, NOAA
o GLOBAL AEROSOL BACKSCATTER MEASUREMENT PROGRAM	– ARC, GSFC, JPL, LRC, MSFC, AFGL, NOAA
o SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE) STUDY	– MSFC
o CO_2 LASER SPACE QUALIFICATION STUDY	– SPECTRA TECHNOLOGIES, INC. (MSFC)
o INJECTION LOCKING STUDIES FOR CO_2, TEA LASERS	– JPL
o CATALYST STUDIES FOR CO_2 LASERS	– LRC
o ATMOSPHERIC ABSORPTION, SCATTERING, AND TURBULENCE EFFECTS	– ALABAMA A&M UNIVERSITY (MSFC)

SCALE

COHERENT DOPPLER LIDAR EVOLUTION



	OBJ.	PULSE ENERGY.	VEL. RES.	DURATION	COVERAGE	SPATIAL RES.	TEMPORAL RES.	ALT.
CAT	CLEAR AIR TURBULENCE	10 mJ	1 m/s	5 HOURS	1 m x 4,000 Km	1.2 Km	10 SECONDS	10 Km
SSWIM	MESOSCALE WIND MAPPING	10 mJ	1 m/s	5 HOURS	10 Km x 4,000 Km	300m	20 MINUTES	10 Km
GLOBE	BACKSCATTER	2J	N/A	5 HOURS	GLOBAL (PARTIAL)	1 Km	30 MINUTES	10 Km
SCALE	BACKSCATTER AND WIND	2J	1 m/s	5 DAYS	GLOBAL	1 Km	90 MINUTES	185 Km
LAWS	GLOBAL WIND	10 J	1 m/s	2 YEARS	GLOBAL	1 Km	3 DAYS	800 Km

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SCALE

GOALS

- DEFINE THE REQUIREMENTS FOR A DOPPLER LIDAR FLIGHT EXPERIMENT ON A SHUTTLE/SPACELAB MISSION
- FLY A SHUTTLE MISSION TO MEASURE WINDS AND AEROSOL BACKSCATTER FROM SPACE

IN-HOUSE STUDY OBJECTIVES

- DEFINE SCIENCE FOR SCALE SHUTTLE/SPACELAB MISSIONS
- DETERMINE SPACE SUITABILITY OF AN EXISTING LASER SYSTEM
- DEFINE TELESCOPE REQUIREMENTS
- DETERMINE SUBSYSTEMS SUPPORT REQUIREMENTS
- ACCOMMODATIONS ANALYSIS TO DETERMINE "SHOW STOPPERS"
- ENOUGH DEFINITION TO ALLOW ADEQUATE COSTING

SCALE

SCIENCE GOALS

– GLOBAL BACKSCATTER DISTRIBUTION

– WIND MEASUREMENT

– AEROSOL PLUMES (DUST CLOUDS, CIRRUS)

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ENGINEERING GOALS

- SPACE QUALIFY LASER
- BEAM SCANNING
- LAG ANGLE COMP
- SIGNAL PROCESSING
- TELESCOPE/OPTICS

SCALE

SHUTTLE ACCOMMODATIONS

- USE EXISTING LASER DESIGN
- FIXED POINTING TELESCOPE
- SPACELAB EXPERIMENT

SCIENCE DESCRIPTION

SCALE Science Goals

- Global Backscatter Distribution
- Wind Measurement
- Aerosol/Cloud Structure Measurement
- Species/DIAL Development

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Aerosol Backscatter at CO2 Wavelengths Research Priorities:

1. Magnitude
2. Climatology
3. Global Distribution
4. Spectral Dependence

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Aerosol Backscatter: Present Sources

1. Ground based and airborne
   a. Microphysics
   b. Other wavelengths
   c. CO_2 Lidars

2. Satellite
   a. SAGE I/SAM
   b. SAGE II

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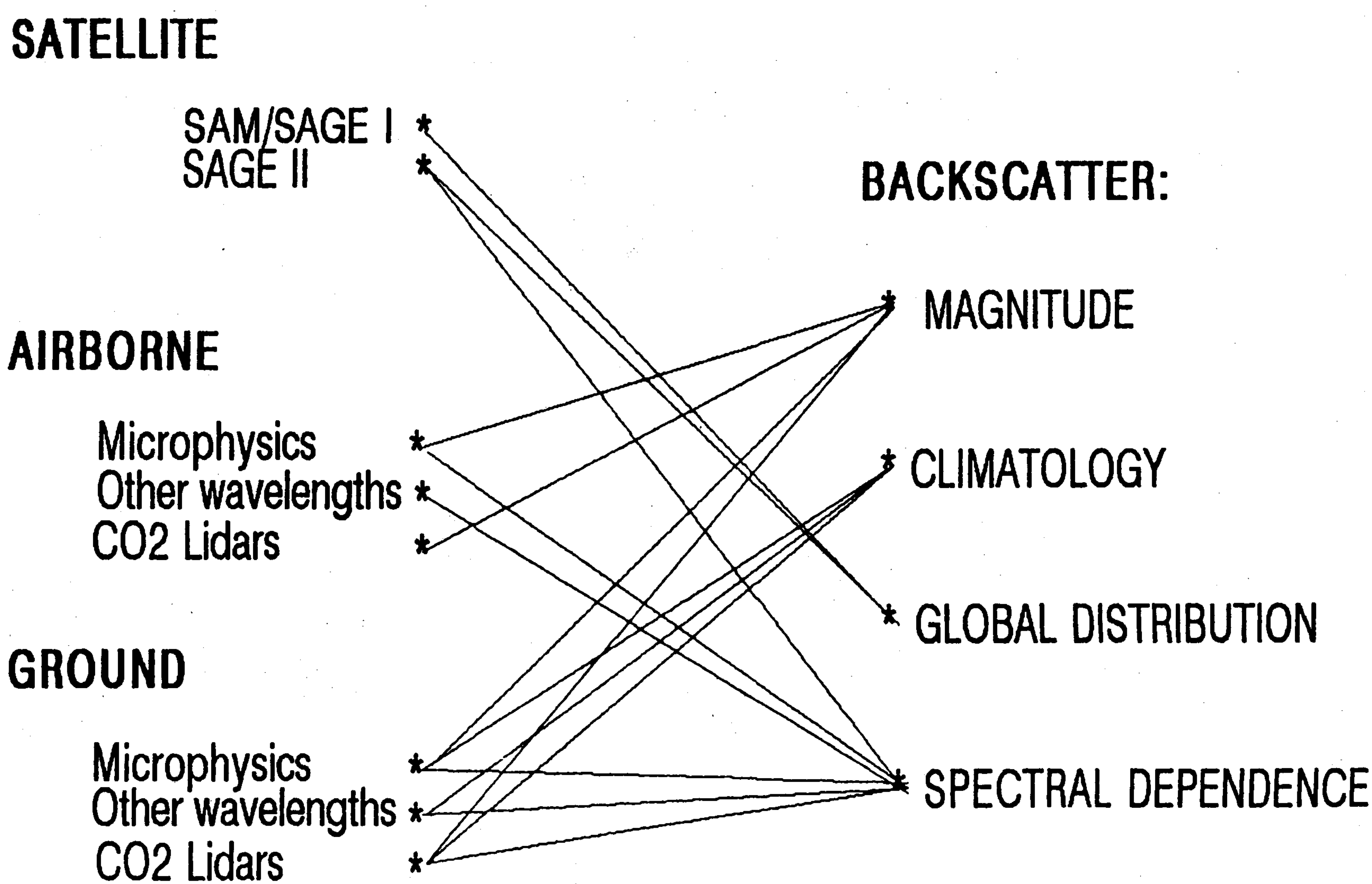
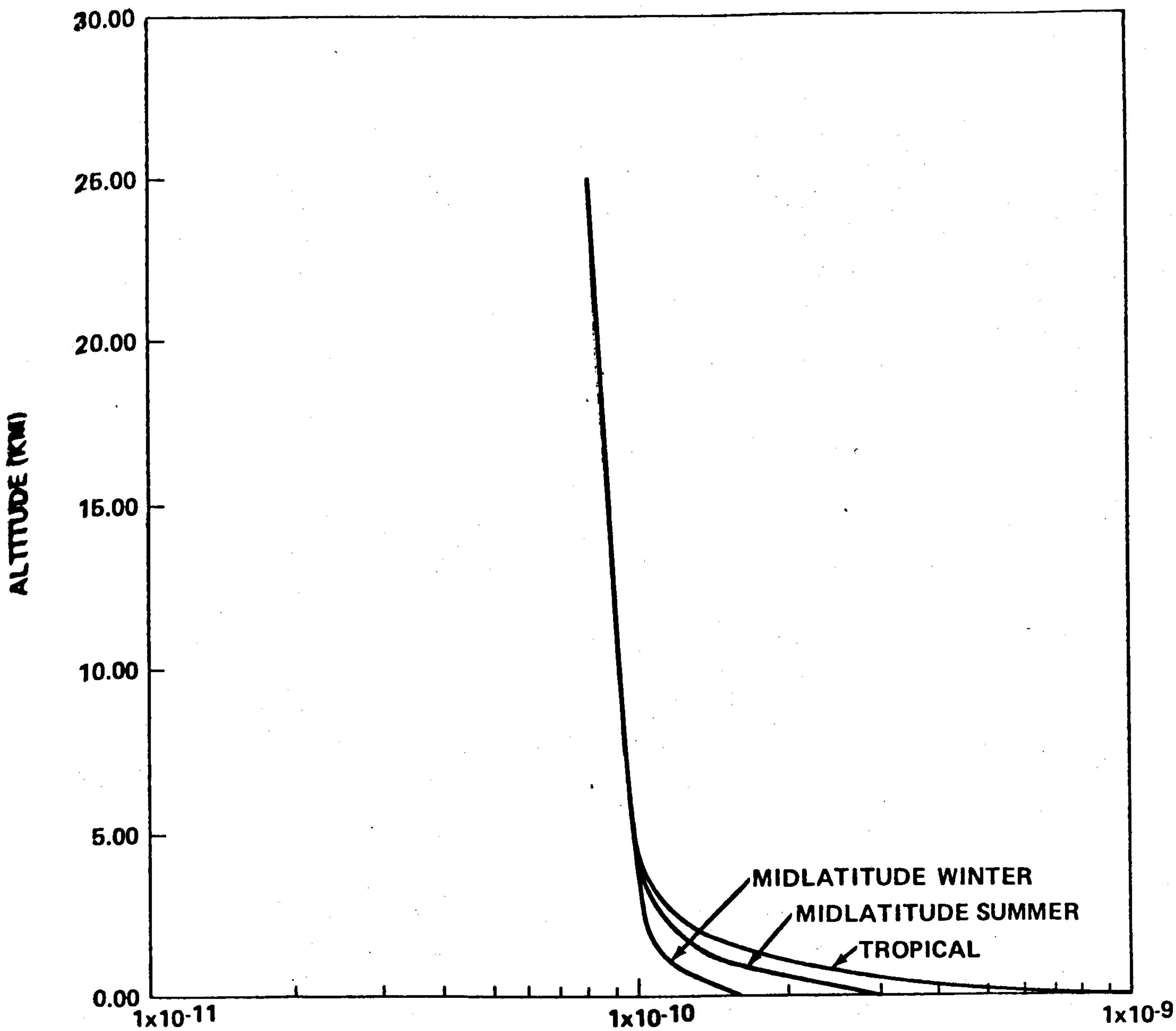

SATELLITE
SAM/SAGE I
SAGE II
AIRBORNE
Microphysics
Other wavelengths
CO2 Lidars
GROUND
Microphysics
Other wavelengths
CO2 Lidars
BACKSCATTER:
MAGNITUDE
CLIMATOLOGY
GLOBAL DISTRIBUTION
SPECTRAL DEPENDENCE

SCALE

Backscatter/Aerosols

1. Backscatter
   a. Sensitivity just above background
   b. Global data set, spatial & temporal
   c. Directly applicable to wind Lidar
2. Enhanced Regions
   - Dust clouds/transport
   - Cirrus
   - Cloud tops/velocities
   - Stratospheric events (volcanic, etc.)
   - Pollution/Haze episodes
   - Boundary layer distribution

SCALE SENSITIVITY 9.11 MICRONS



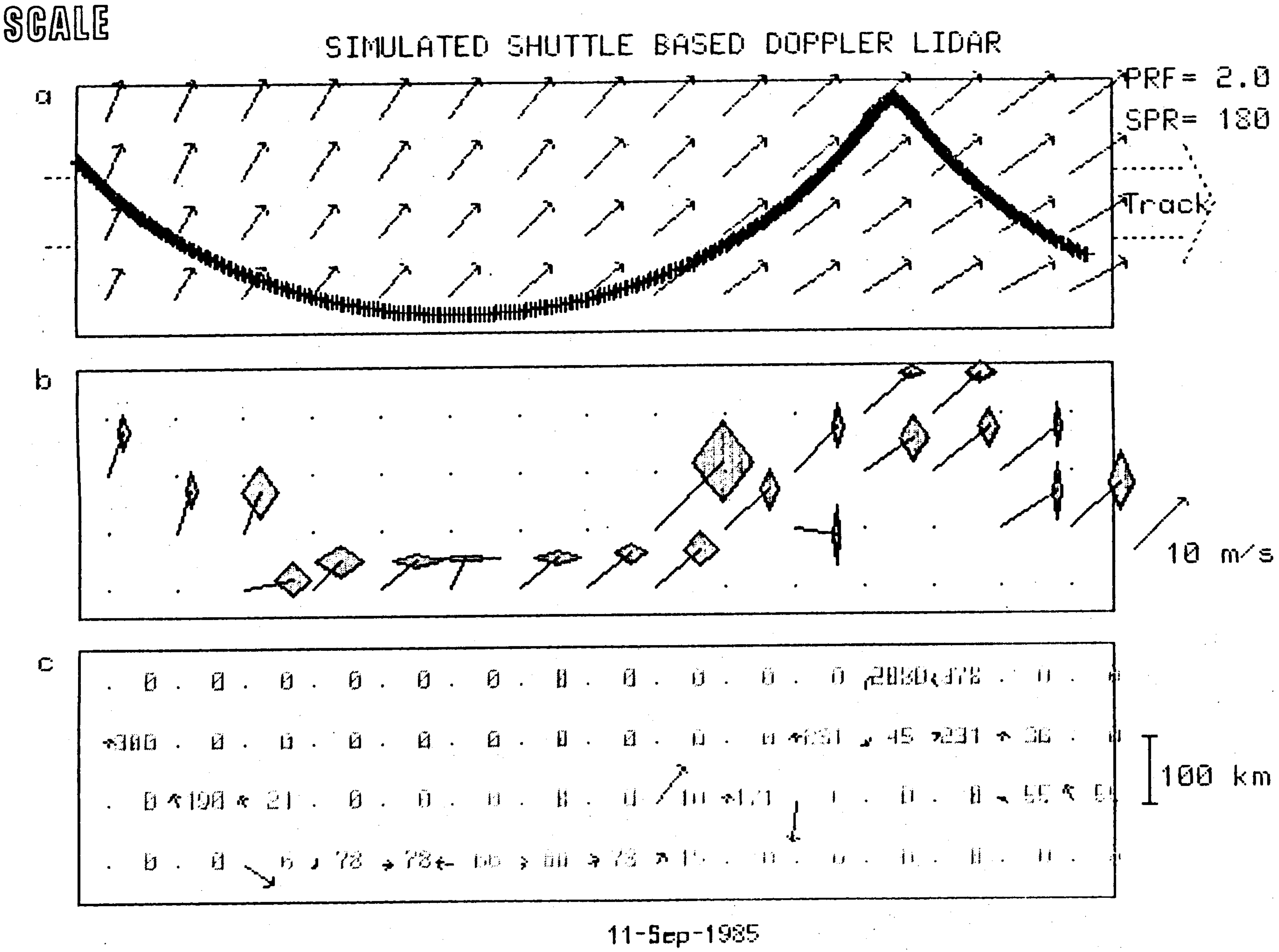
BACKSCATTER COEFFICIENT ($M^{-1}SR^{-1}$)
185 KM ORBIT 45 DEGREES FROM NADIR
INCLUDES AEROSOL EXTINCTION FROM HAZE-C MODEL

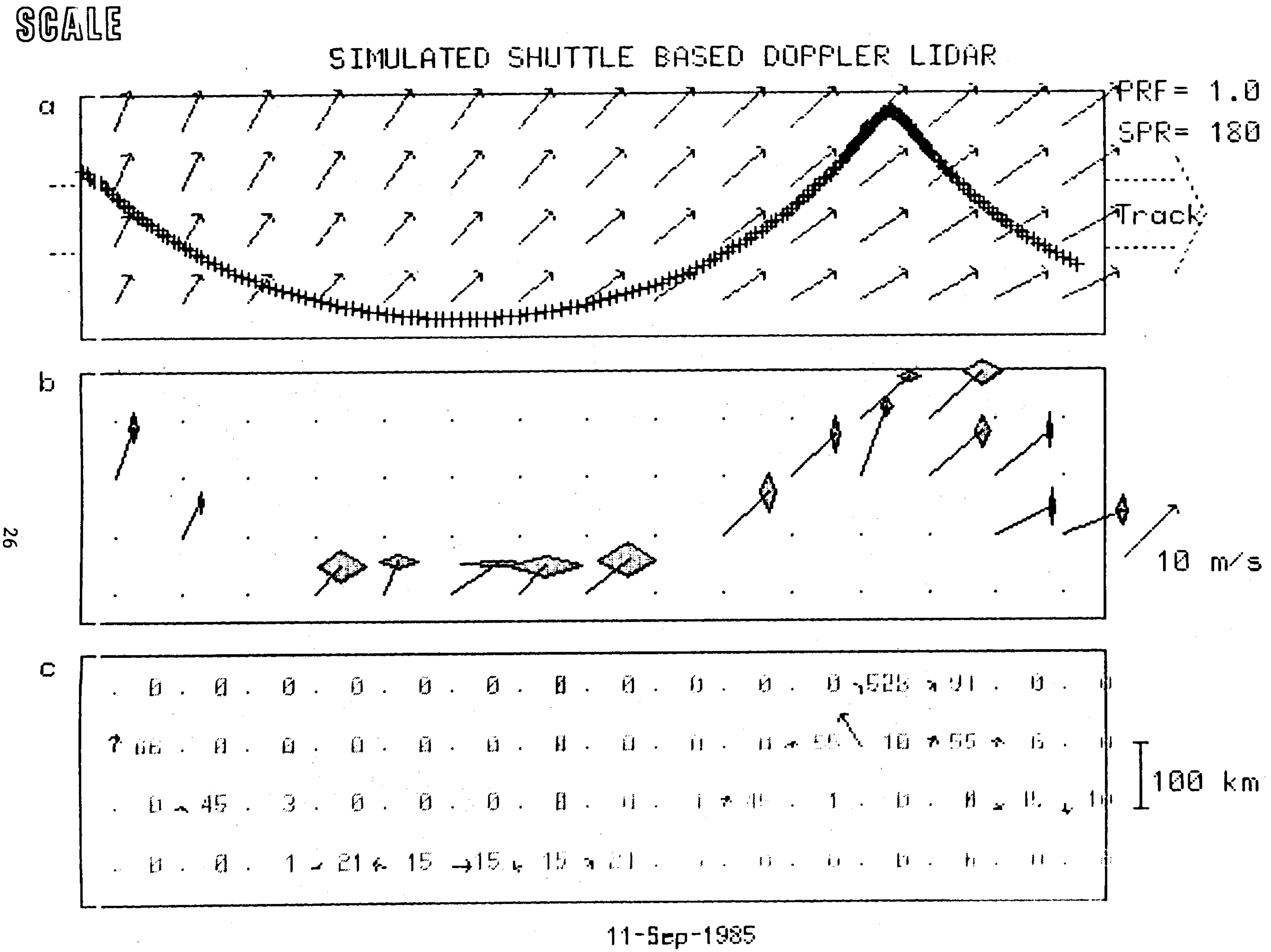
Wind Measurements with SCALE

1. Technique
   a. Scanning
   b. Data processing/interpretation

2. Global wind data set
   a. Wind vectors
   b. Line – of – sight components


SHUTTLE COHERENT
ATMOSPHERIC LIDAR
EXPERIMENT (SCALE)
PULSED
LIDAR
SYSTEM
BACKSCATTERED
RADIATION
DOPPLER SHIFTED
BACKSCATTERING
AEROSOLS
MOVE WITH WINDS


SCALE
SIMULATED SHUTTLE BASED DOPPLER LIDAR
PRF= 2.0
SPR= 180
Track
a
b
c
10 m/s
100 km
11-Sep-1985


SCALE
SIMULATED SHUTTLE BASED DOPPLER LIDAR
PRF = 1.0
SPR = 180
Track
a
b
c
10 m/s
100 km
11-Sep-1985

SCALE

SCALE WINDFIELD USES

1. Ground – truth cooperative measurements
2. Validation of Observing System Simulation Studies
3. Comparison of continuous line – of – sight winds with model output
4. Two rotations per orbit allow calculation of winds in a 3000 km strip along orbit
5. Successive orbits trace out a band of winds around the globe for data assimilation studies

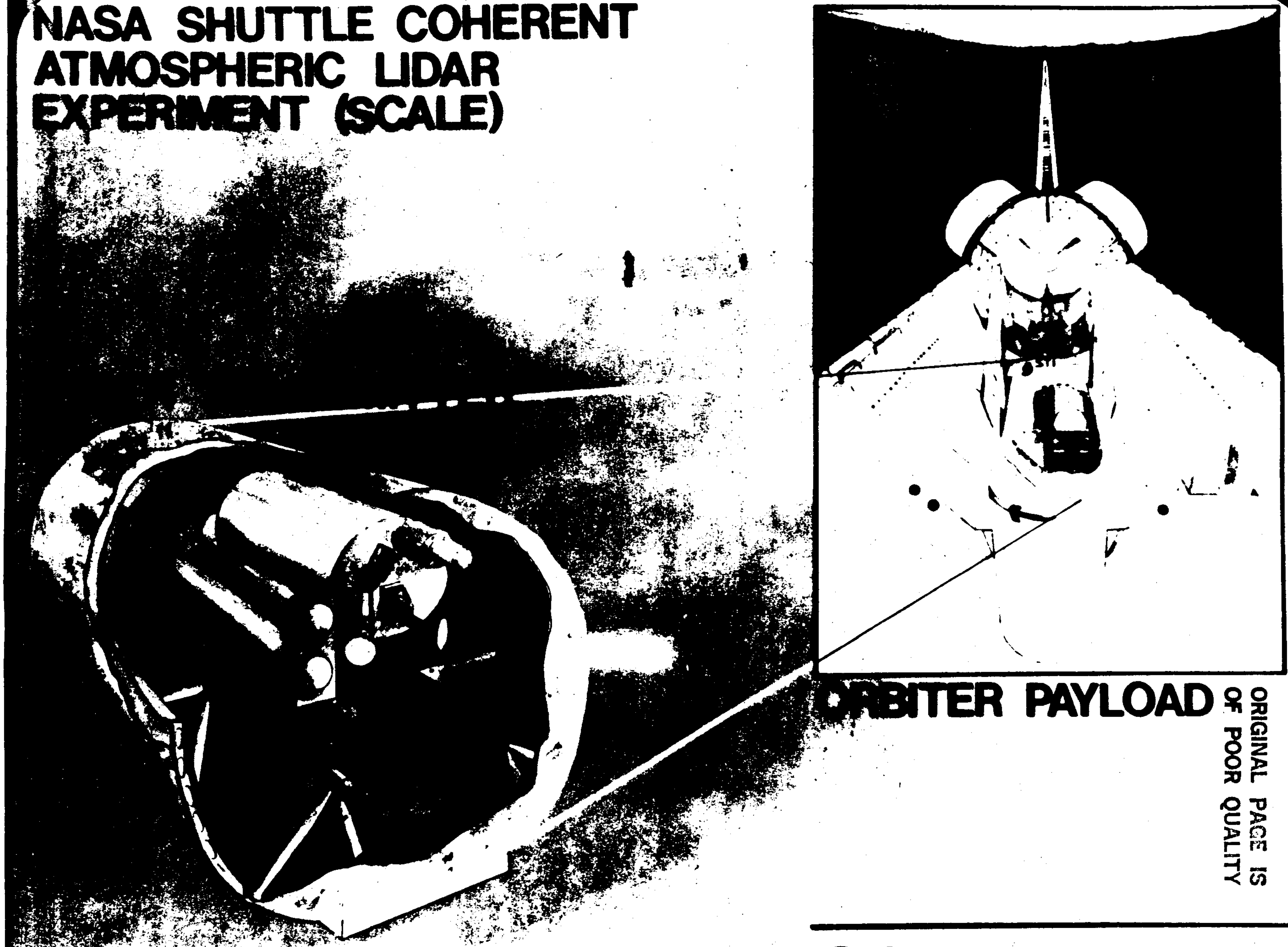
Species Measurement with CO_2

1. DIAL Possibilities
   a. Ammonia (only laser candidate)
   b. Water Vapor (demonstrated by NOAA)
   c. Ozone
   d. Carbon Monoxide

2. SCALE
   a. Laboratory demonstration
   b. Design space hardware for addition
   c. Reflights with DIAL

SCALE INSTRUMENT DESCRIPTION

NASA SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)



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Spectra Technology

SCALE

ENGINEERING GOALS

- SPACE QUALIFY LASER
- BEAM SCANNING
- LAG ANGLE COMP
- SIGNAL PROCESSING
- TELESCOPE/OPTICS

SCALE

- SYSTEM SENSITIVITY
- LASER
- TELESCOPE
- SIGNAL PROCESSING

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SCALE SYSTEM PARAMETERS

LASER

2 JOULE PULSE ENERGY
25Hz REPETITION RATE
5 μs PULSE DURATION
9.11 μm WAVELENGTH
10^7 SHOT LIFETIME
NONRECYCLING OPERATION

OPTICS:

1.25 METER APERTURE
DIFFRACTION LIMITED
FIXED POINTING
LAG ANGLE COMPENSATED

POINTING:

SHUTTLE ACCURACY ($\pm .50^\circ$)

FOCAL PLANE:

Hg CdTe DETECTOR
CRYOGENIC COOLED
SHUTTLE MOTION CORRECTED

SIGNAL PROCESSING:

ONBOARD FFT PROCESSING
REALTIME DATA TRANSFER

POWER REQUIREMENTS (W)

LASER	–1,375
FOCAL PLANE	– 38
SIGNAL PROCESSING	– 186
SUPPORT STRUCTURE	– 26
COOLING	– 315
	2,040

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SENSITIVITY ANALYSIS

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SCALE SENSITIVITY

$$\mathrm{SNR} = \frac{\pi \eta J \beta C \tau D^2 K U O e^{-2\mu(R-A)\sec\theta}}{8h\nu\left[\{(R-A)\sec\theta\}^2 + \left(\frac{\pi D^2}{4\lambda}\right)^2 \left(\frac{1-(R-A)\sec\theta}{f}\right)^2\right]}$$

η = SYSTEM EFFICIENCY = 10%
J = PULSE ENERGY = 2 JOULES
β = BACKSCATTER COEFFICIENT = DESIRED PARAMETER
C = SPEED OF LIGHT = 3×10^8 m/s
τ = PULSE DURATION = 5×10^{-6}s
D = APERTURE DIAMETER = 1.25 m
K = TRUNCATION FACTOR = .46
U = UNSTABLE RESONATOR CONFIGURATION LOSS = .7
O = OBSCURATION LOSS –
μ = ATMOSPHERIC ABSORPTION COEFFICIENT = AFGL MODEL
R = ORBIT ALTITUDE = 185 Km
A = HEIGHT ABOVE GROUND
θ = ANGLE FROM NADIR = 45^o
$n\nu$ = PHOTON ENERGY = 2.182×10^{-20} JOULES
λ = WAVELENGTH = 9.11×10^{-6}m
f = FOCAL DISTANCE = ∞
SNR = 5 dB

SCALE

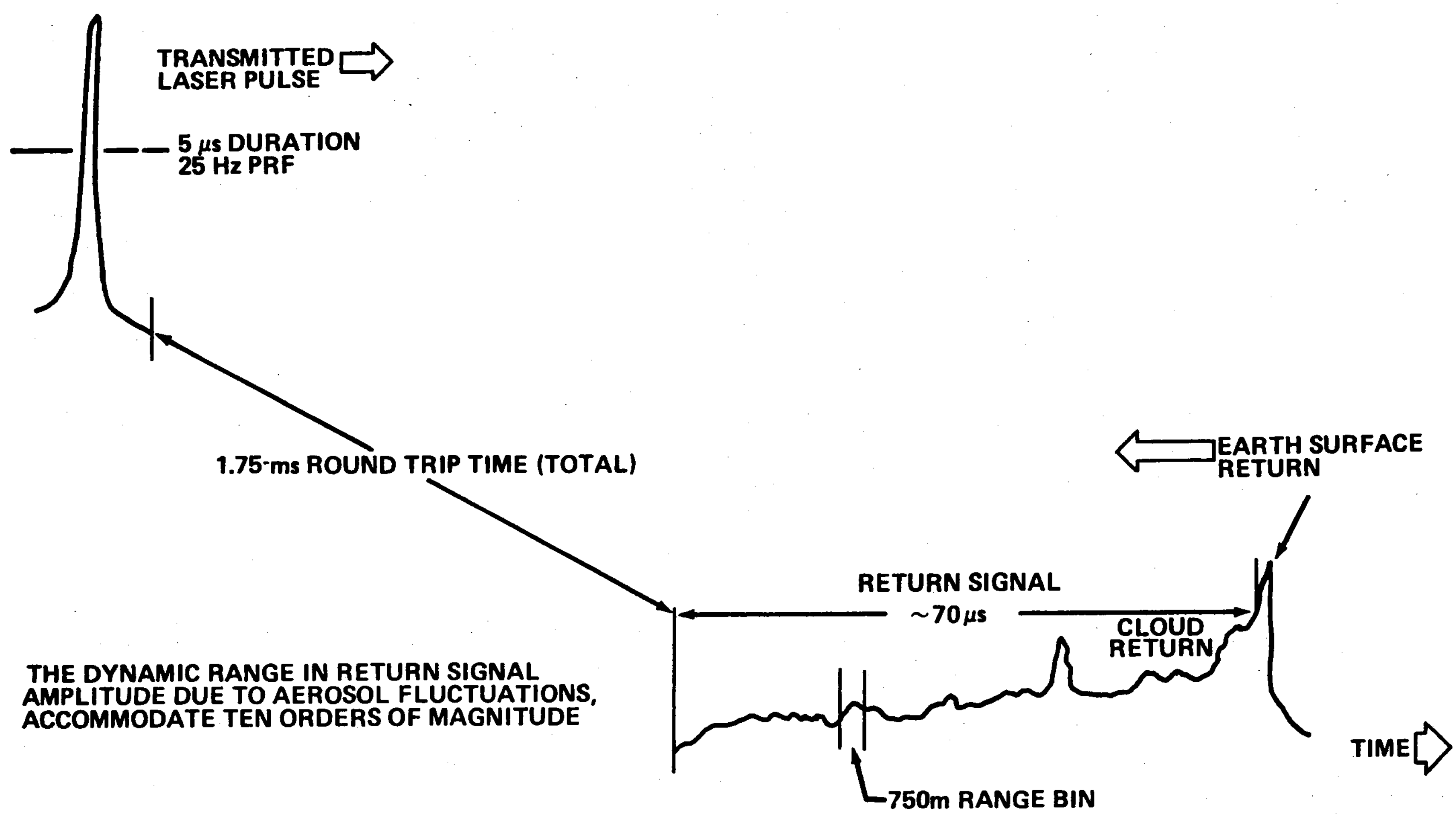
SCALE SENSITIVITY CONTINUED

$\beta = 1.16 \times 10^{-21} \left[(261630 - 1.414A)^2 + 1.815 \times 10^{10}\right] e^{1.414\alpha}$

A = HEIGHT ABOVE GROUND

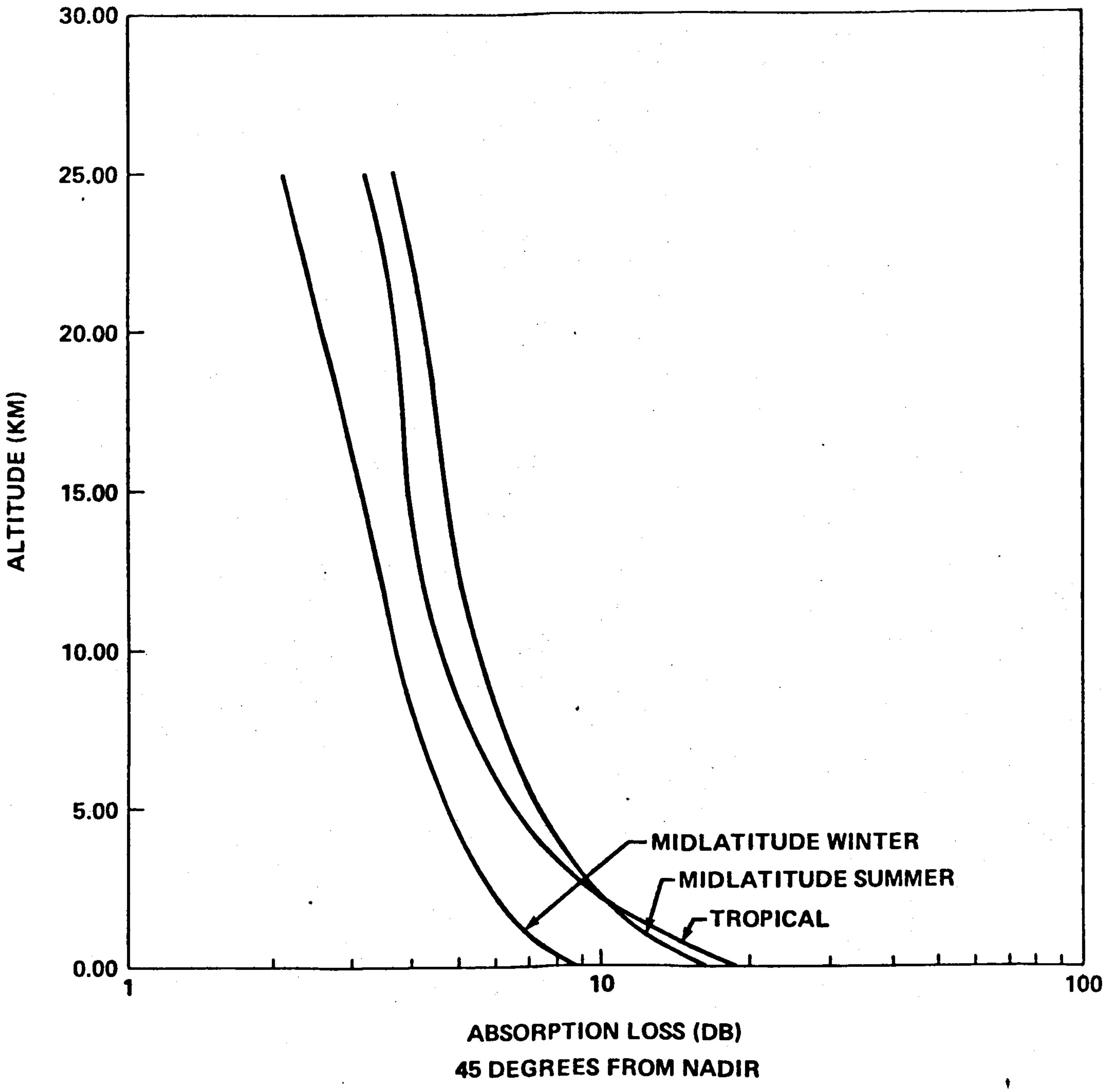
α = TOTAL INTEGRATED ABSORPTION/EXTINCTION FOR A ROUND TRIP VERTICAL PATH FROM ORBIT TO HEIGHT A.

SCALE



TRANSMITTED
LASER PULSE
5 μs DURATION
25 Hz PRF
1.75-ms ROUND TRIP TIME (TOTAL)
EARTH SURFACE
RETURN
RETURN SIGNAL
~70 μs
CLOUD
RETURN
TIME
750m RANGE BIN
THE DYNAMIC RANGE IN RETURN SIGNAL
AMPLITUDE DUE TO AEROSOL FLUCTUATIONS,
ACCOMMODATE TEN ORDERS OF MAGNITUDE

ABSORPTION LOSS FOR 10.6 MICRONS



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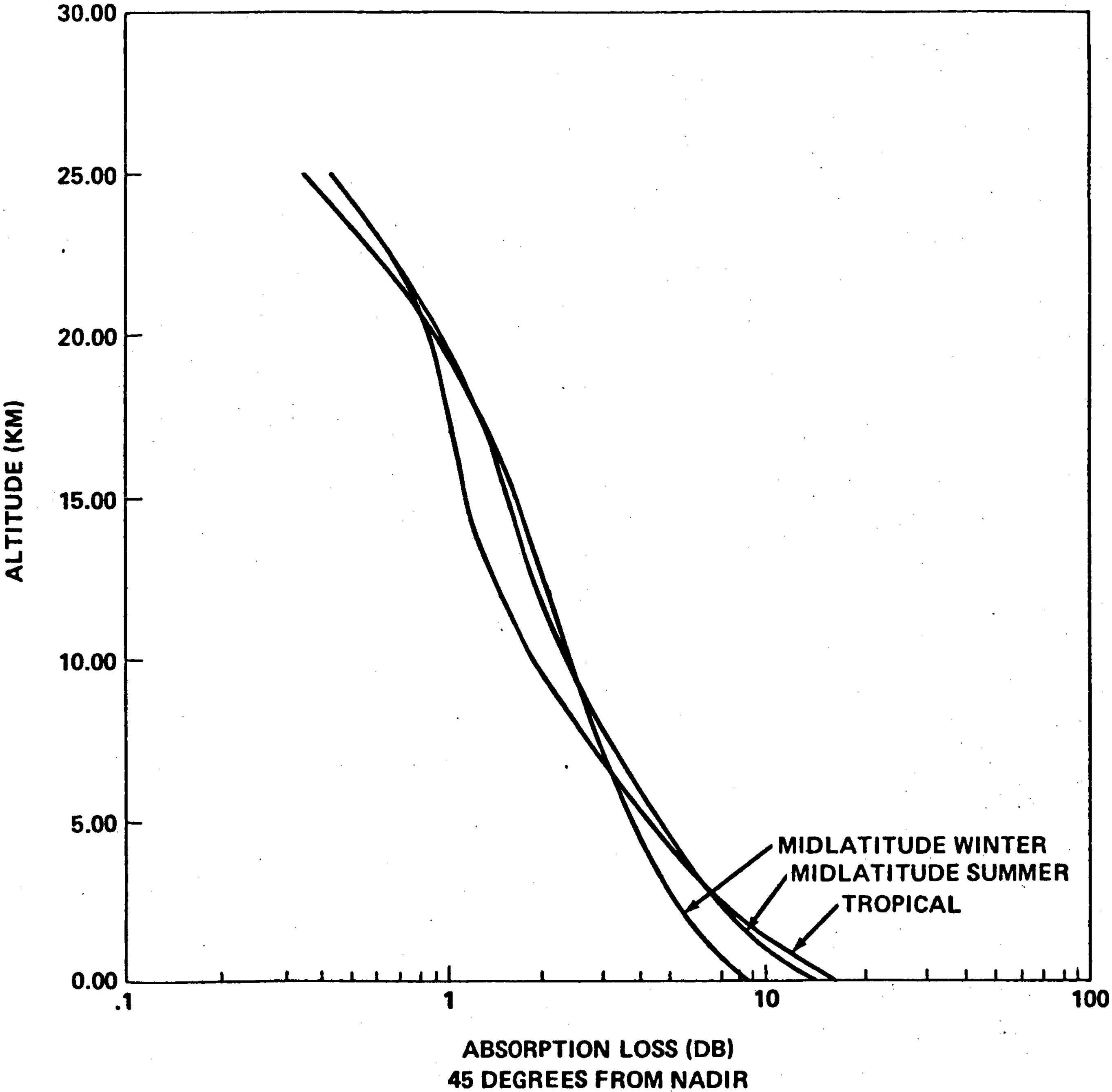
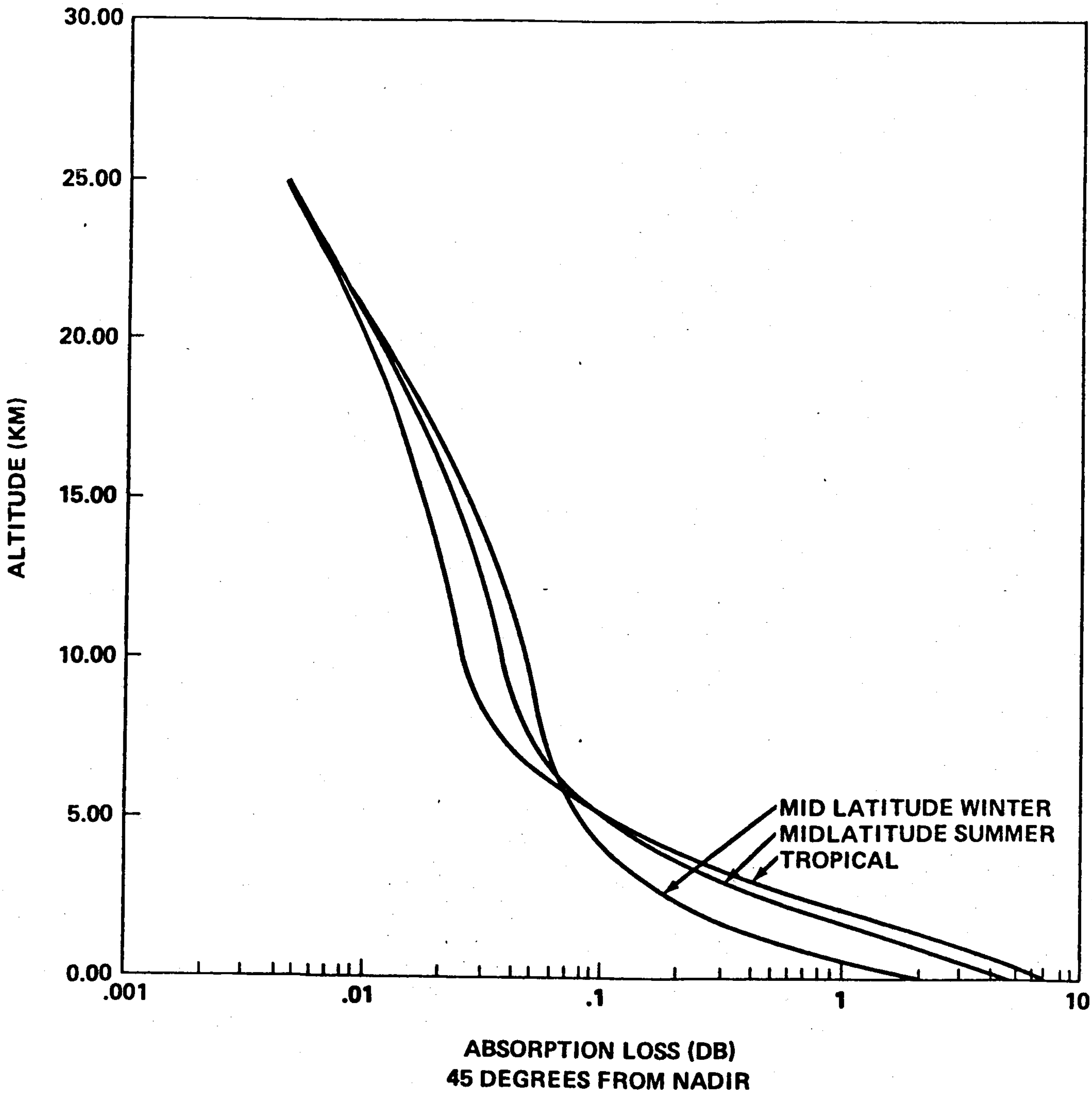
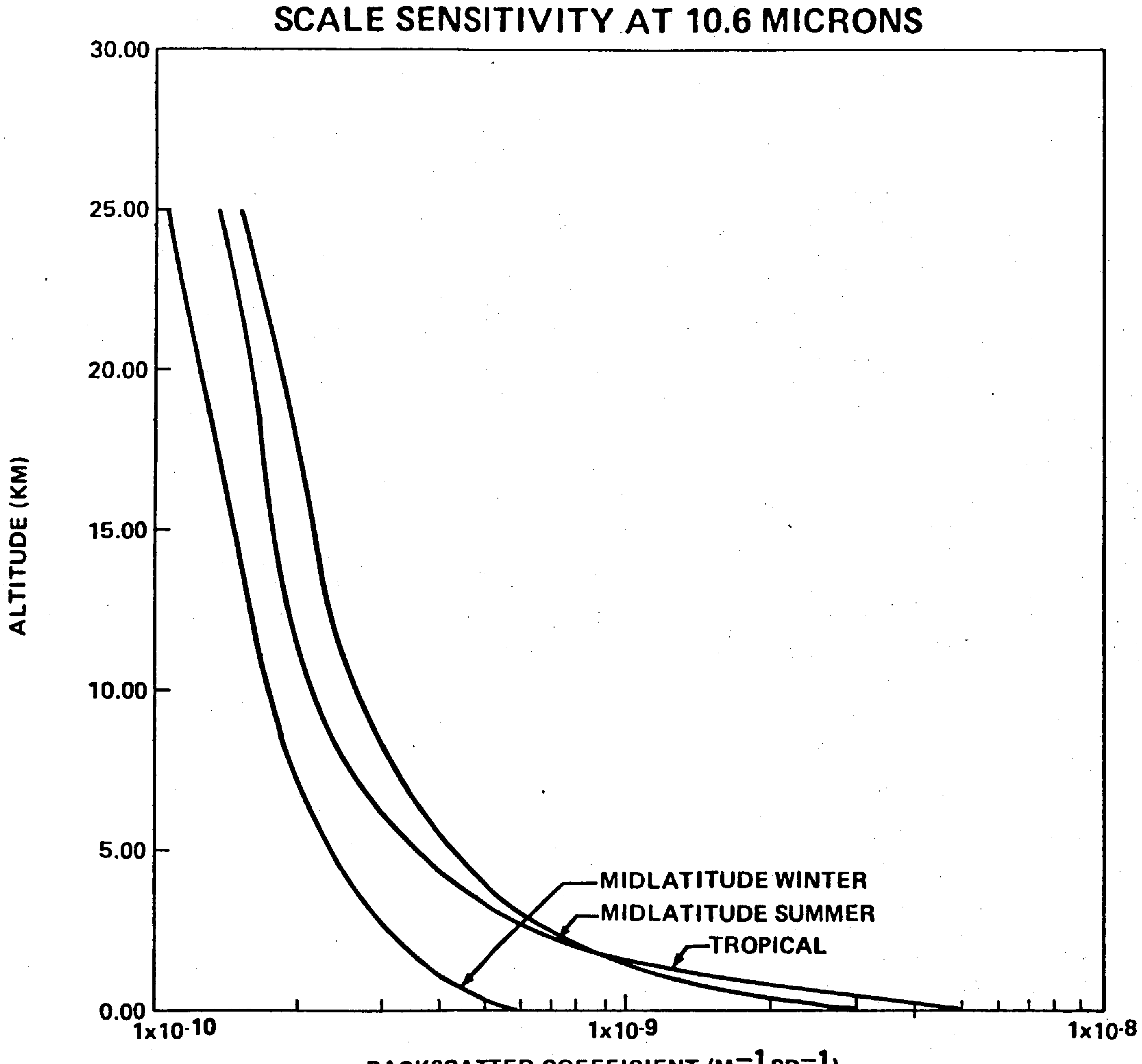
ABSORPTION LOSS FOR 9.25 MICRONS



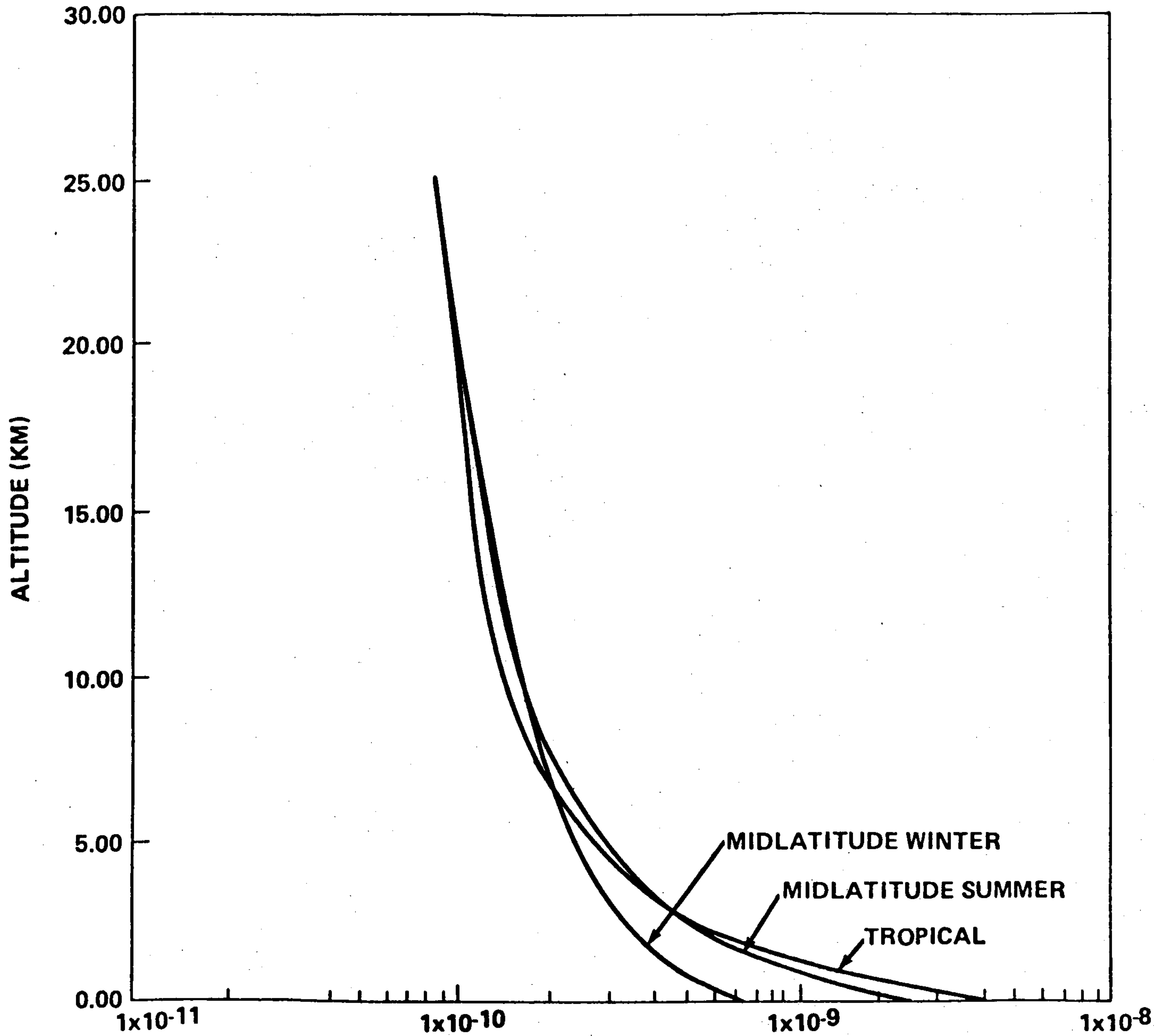
ABSORPTION LOSS FOR 9.11 MICRONS



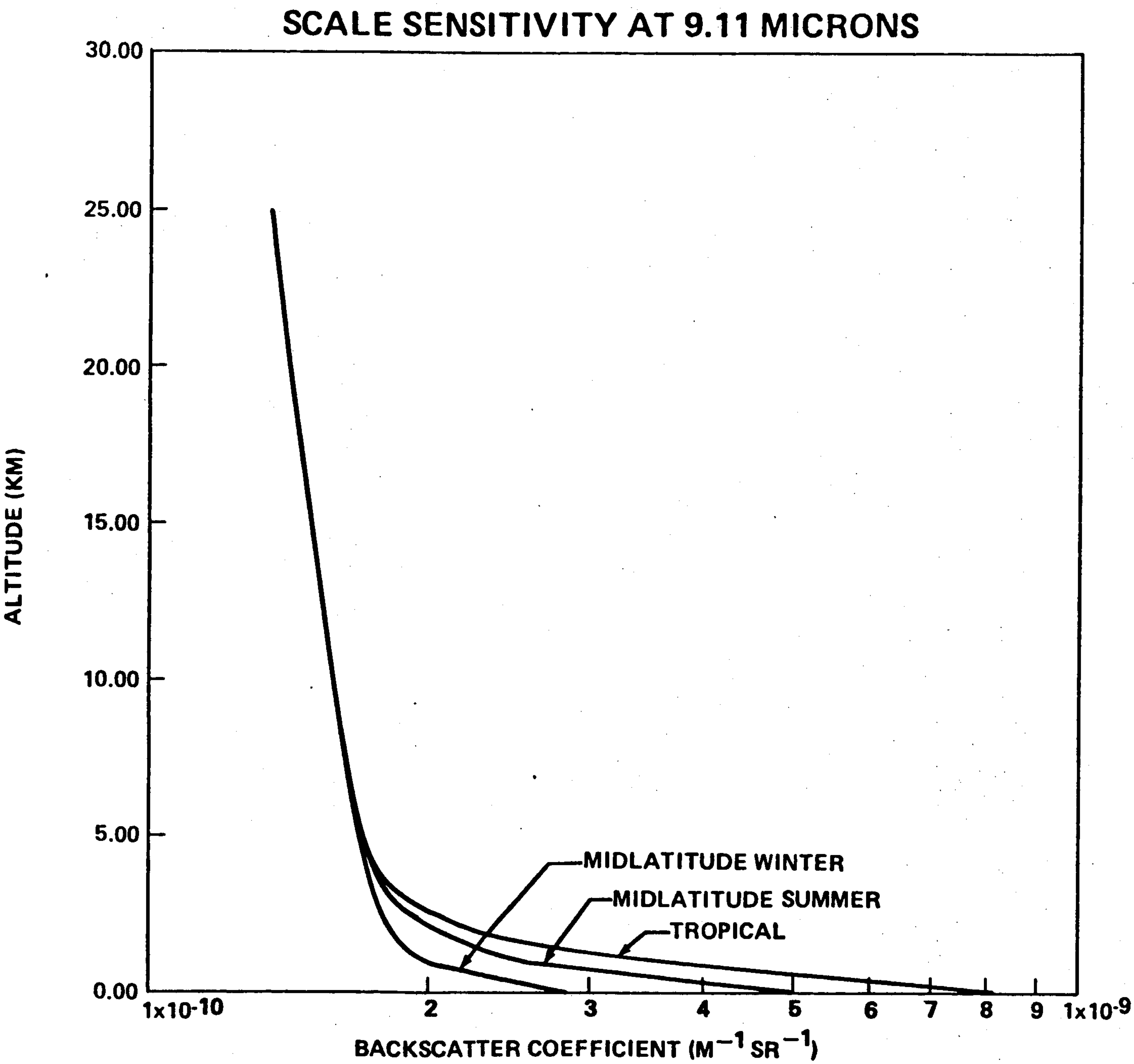


185 KM ORBIT 45 DEGREES FROM NADIR
INCLUDES AEROSOL EXTINCTION FROM HAZE-C MODEL

SCALE SENSITIVITY AT 9.25 MICRONS

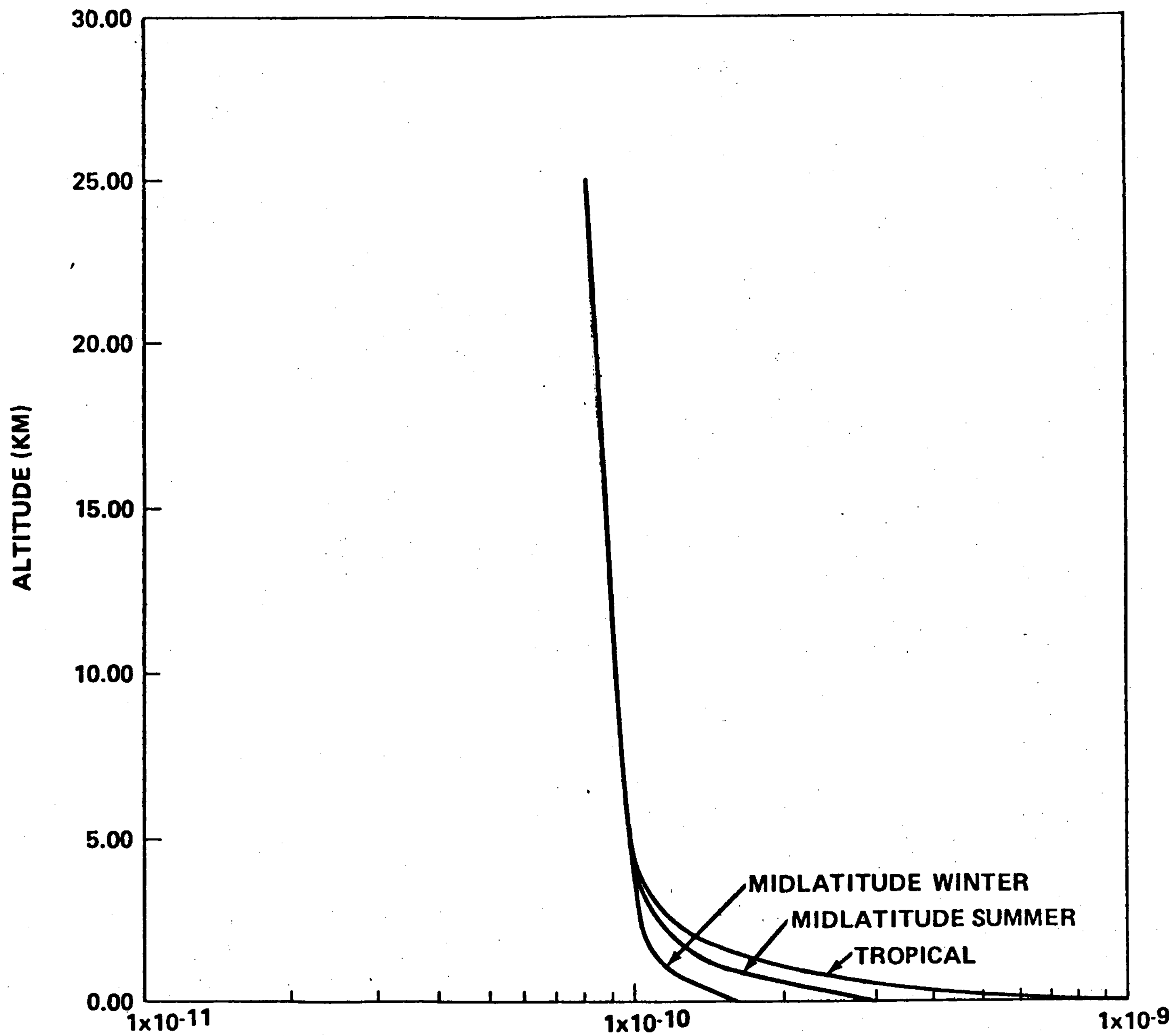


BACKSCATTER COEFFICIENT ($M^{-1}SR^{-1}$)
185 KM ORBIT 45 DEGREES FROM NADIR
SCALE SENSITIVITY AT 9.11 MICRONS



185 KM ORBIT 45 DEGREES FROM NADIR LITE TELESCOPE
INCLUDES AEROSOL EXTINCTION FROM HAZE-C MODEL

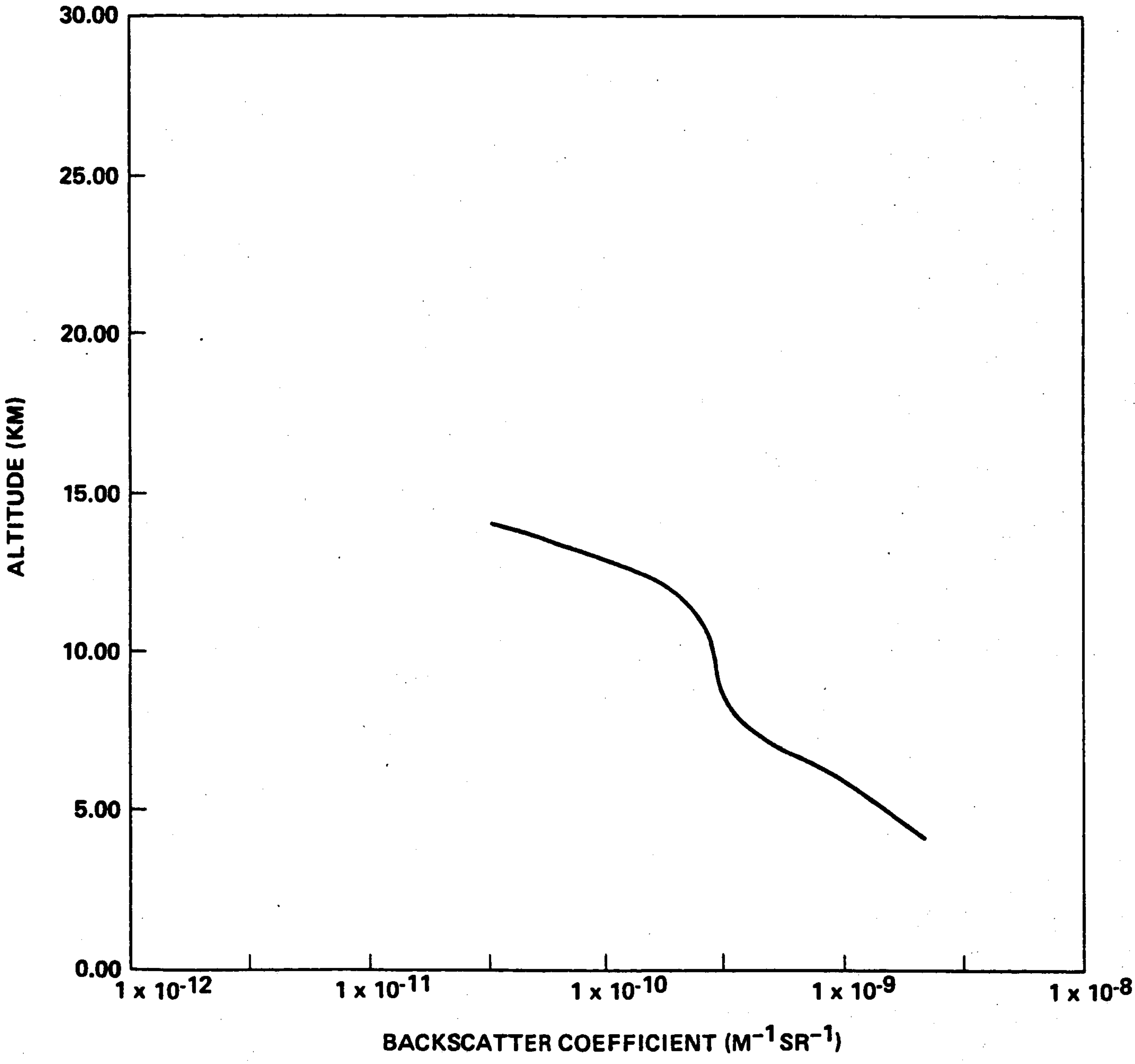
SCALE SENSITIVITY 9.11 MICRONS



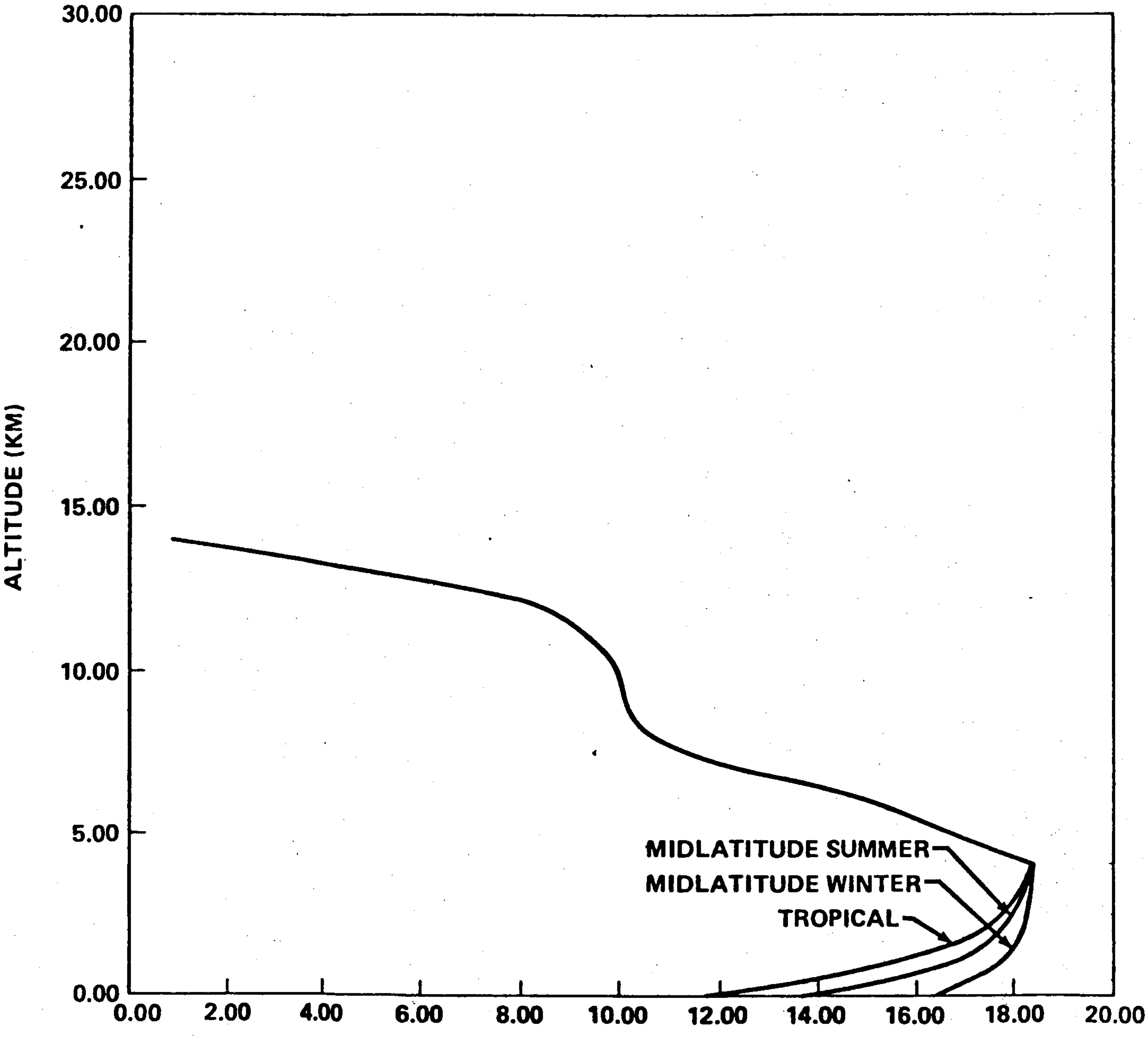
BACKSCATTER COEFFICIENT ($M^{-1}SR^{-1}$)
185 KM ORBIT 45 DEGREES FROM NADIR
INCLUDES AEROSOL EXTINCTION FROM HAZE-C MODEL

SCALE

BACKSCATTER SPRING 84 AVG – POST – 10.6 MICRONS

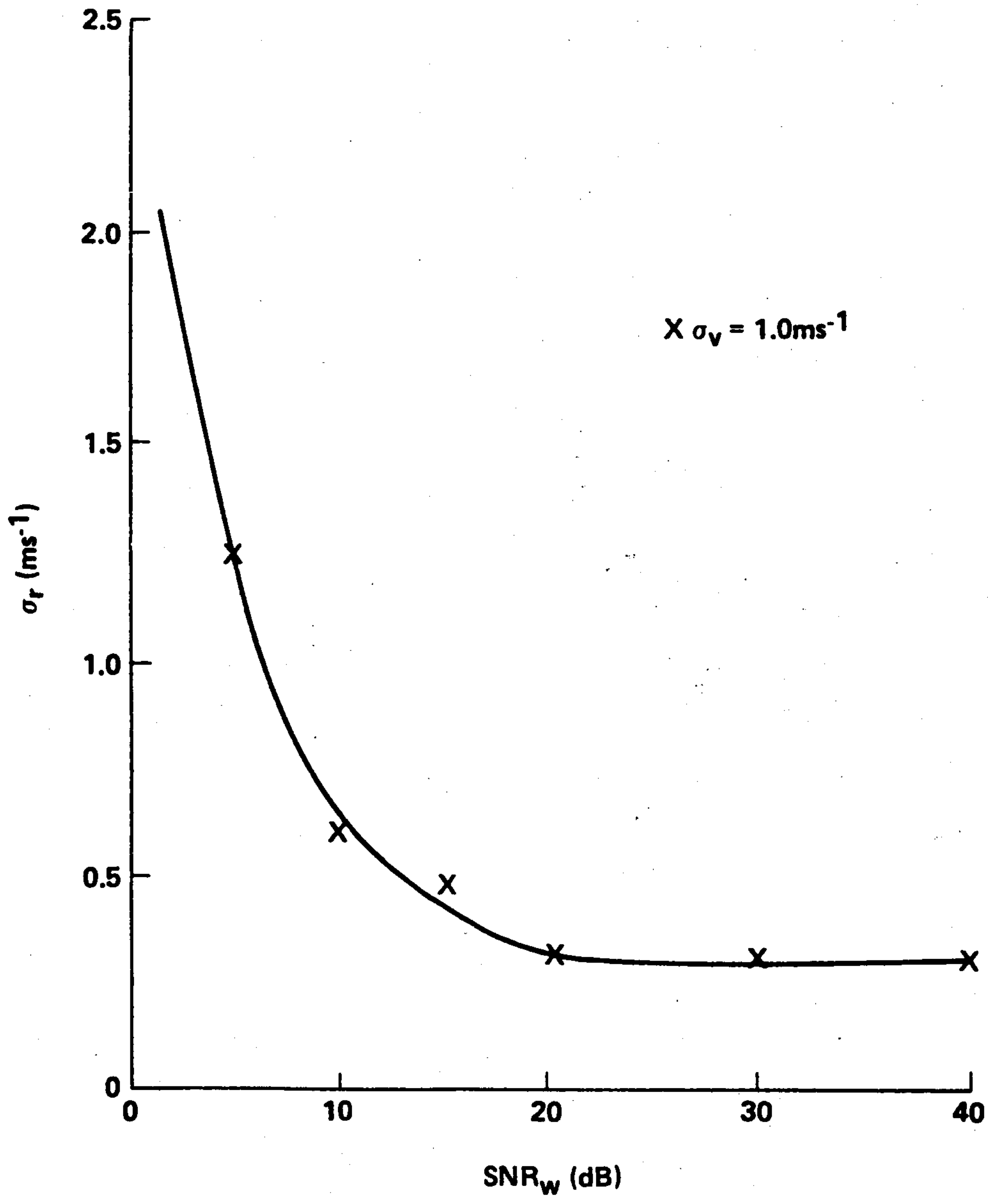


SNR FOR LAMBDA = 9.11 MICRONS



185 KM ORBIT 45 DEGREES FROM NADIR SPRING 84 BETA – POST

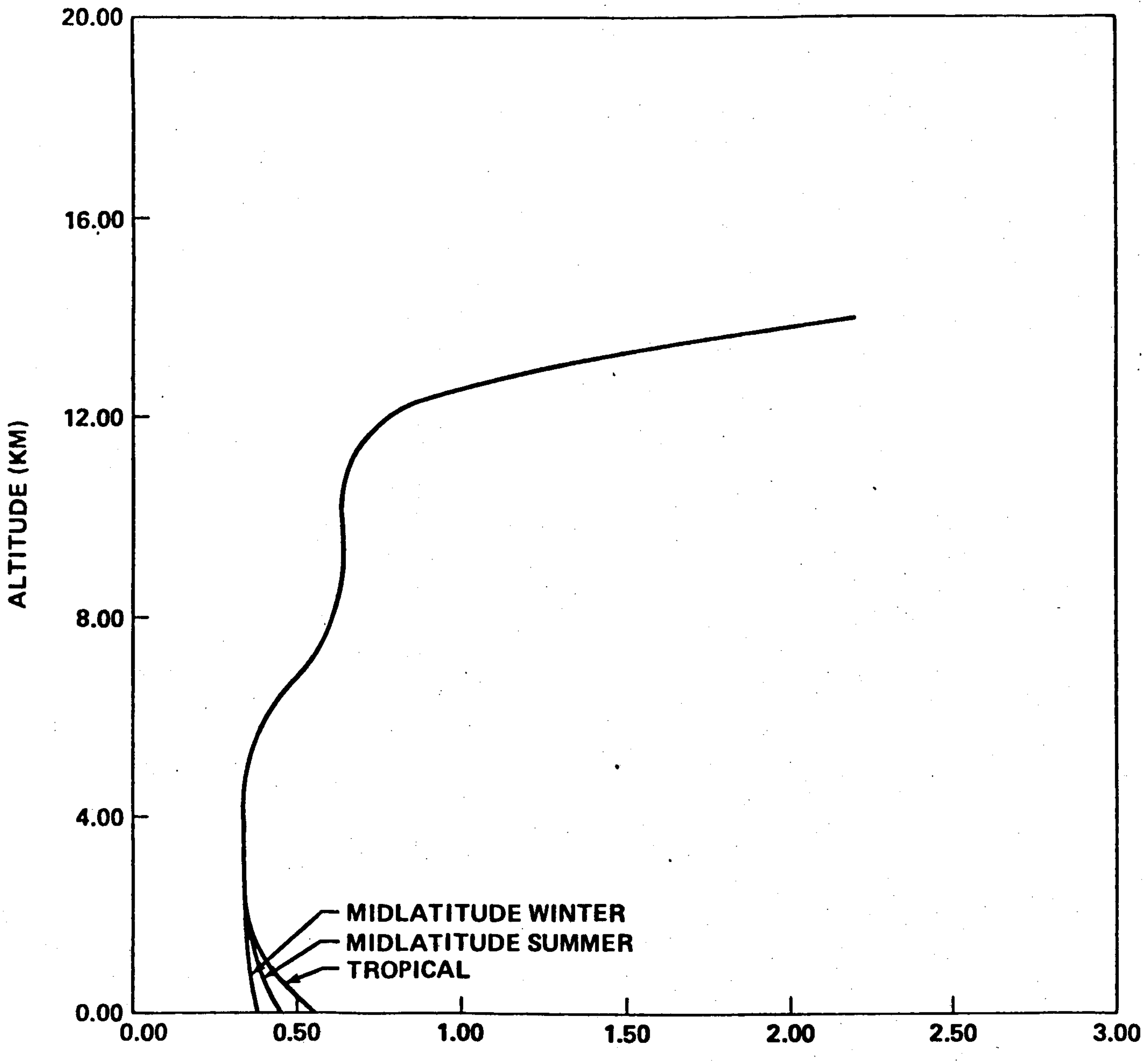
SCALE



RADIAL VELOCITY ERROR FOR ONE SHOT VS. NARROWBAND SIGNAL-TO-NOISE RATIO WITH RMS WIND VELOCITY WIDTH EQUAL 1.0ms^{-1}. V_{max} = 10ms^{-1}.
(NOAA WPL – 63 AUG. 80)

SCALE

RADIAL VELOCITY ERROR FOR 9.11 MICRONS



185 KM ORBIT 45 DEGREES FROM NADIR SIGMA WIND = 1. M/S

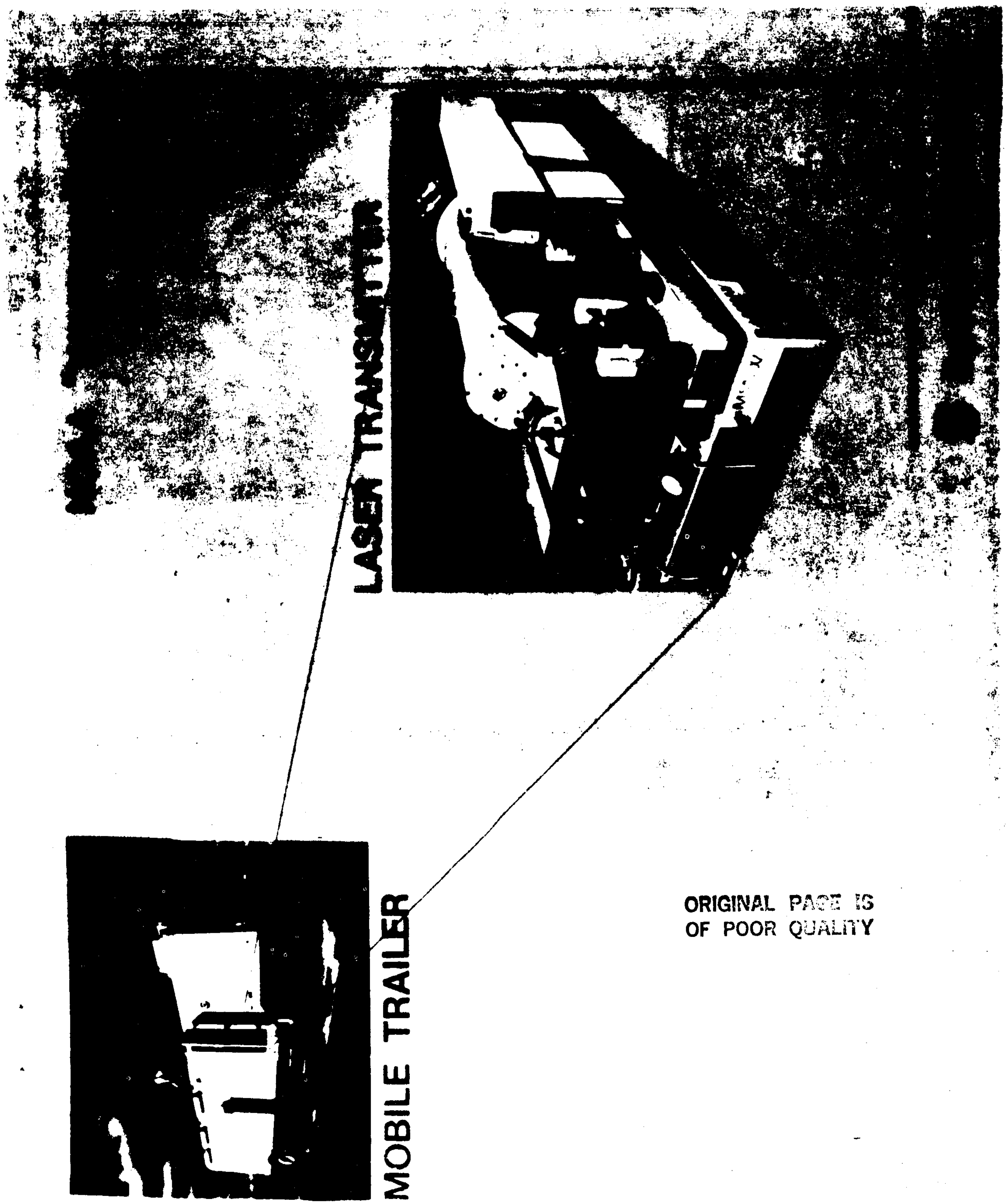
LASER

SCALE

SCALE

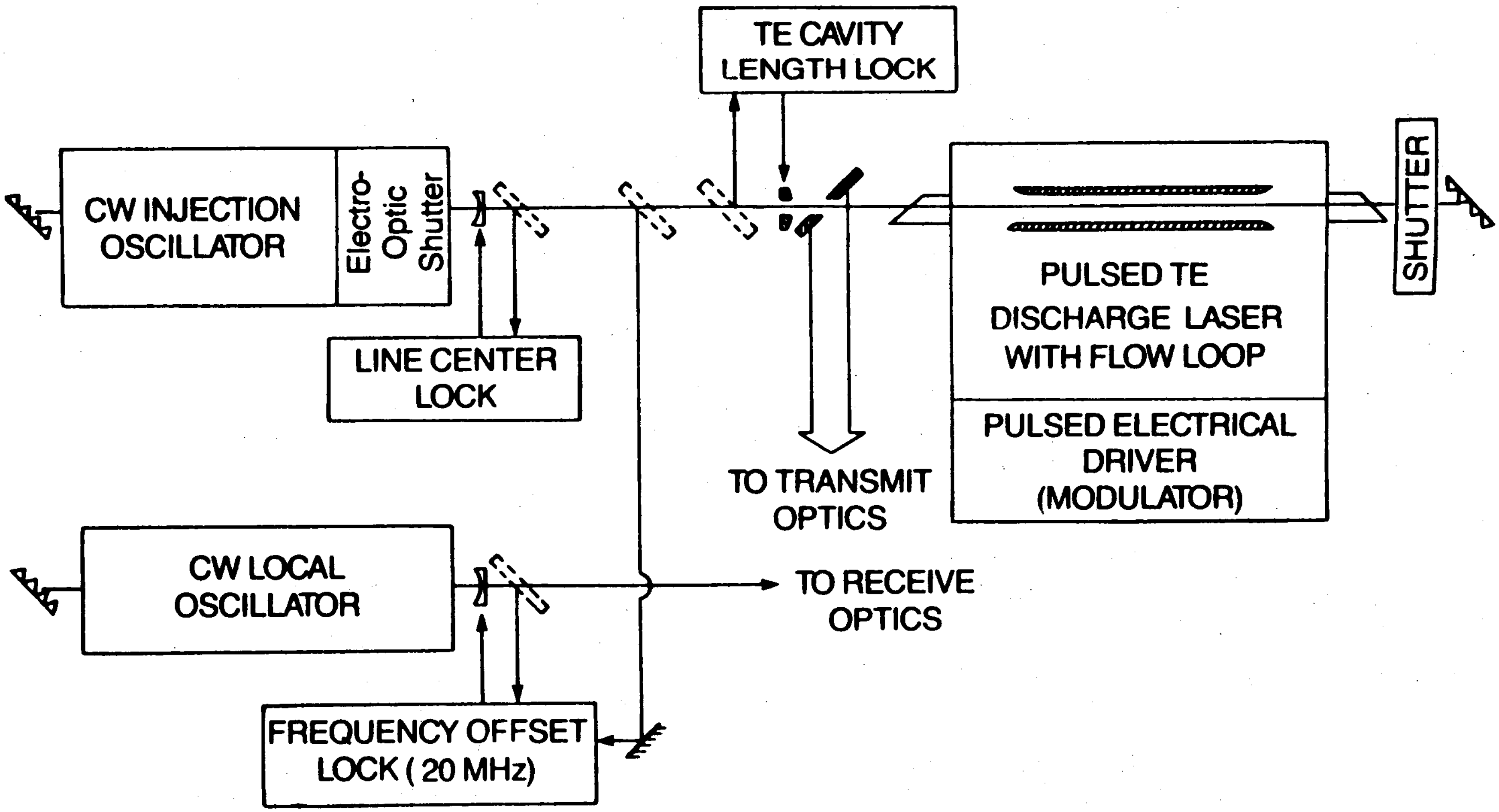
SCALE LASER PARAMETERS

- EXISTING PROVEN DESIGN
- 2J ENERGY
- 25 Hz PRF
- 5μS PULSE
- ISOTOPIC OPERATION
- NON RECYCLING
- 3% WALL PLUG EFFICIENCY
- 10^7 LIFE TIME


LASER TRANSMITTER
MOBILE TRAILER

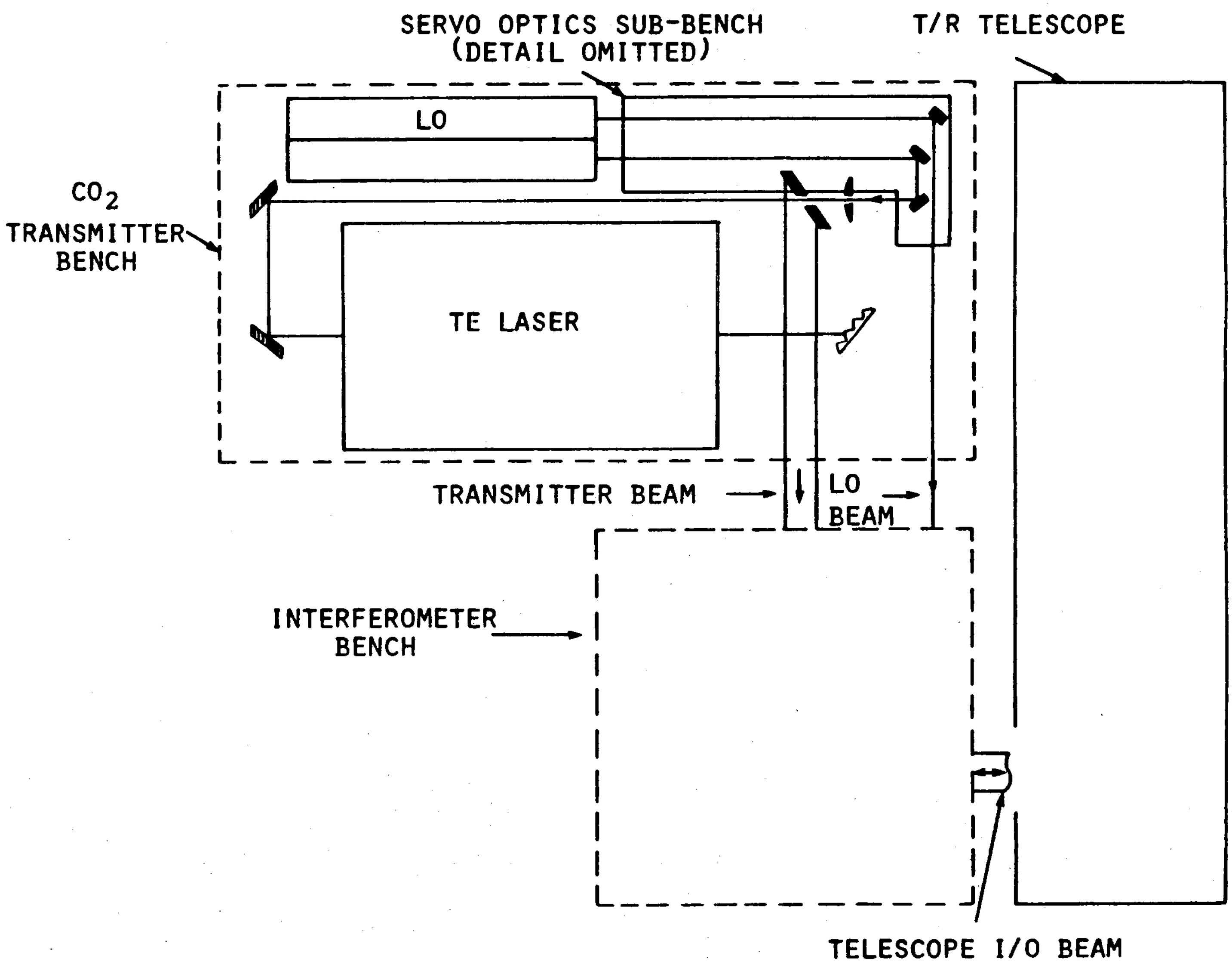
SCALE

CONCEPTUAL DESIGN FOR HIGH AVERAGE POWER LIDAR UPGRADE



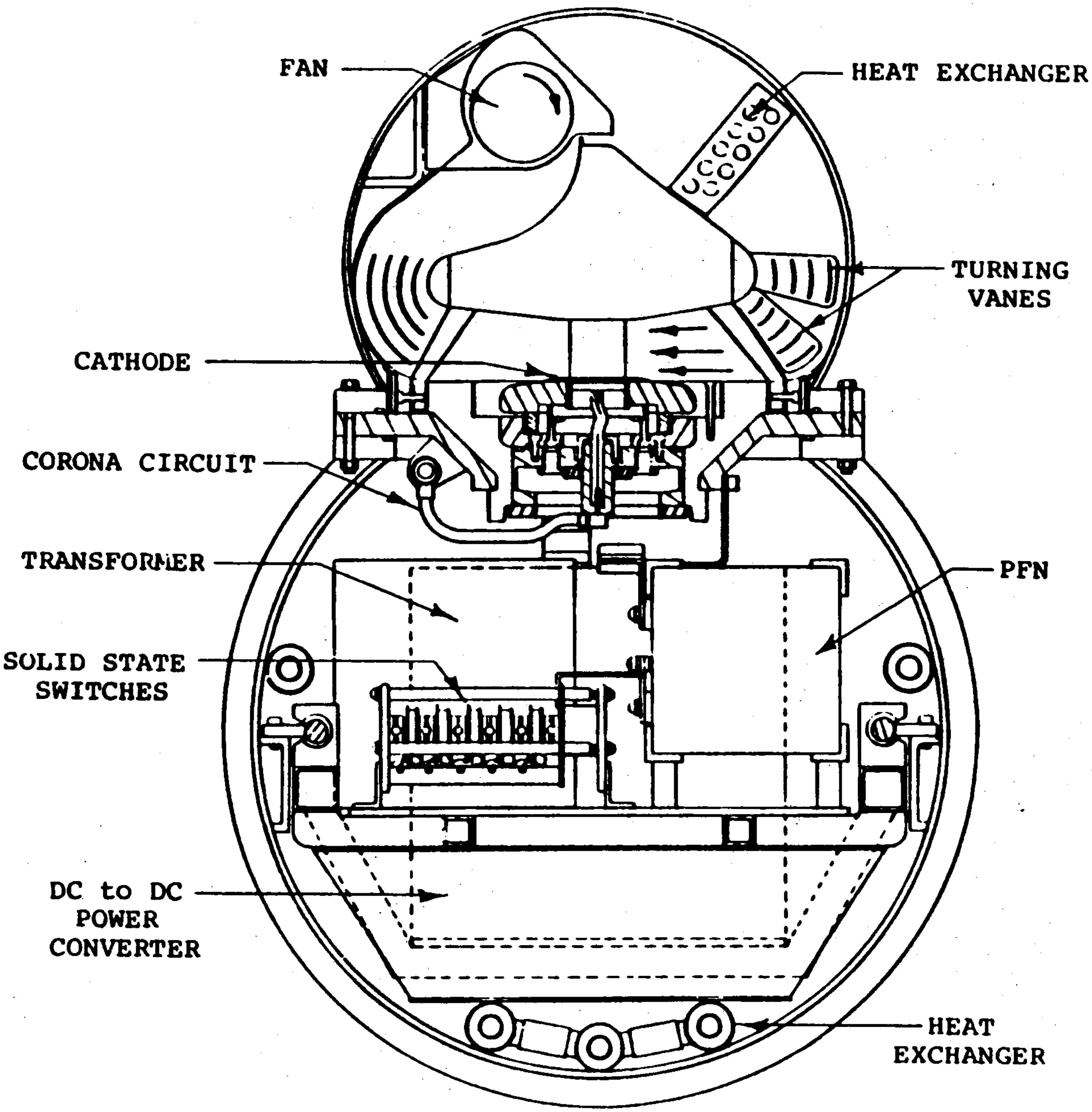
SCALE

DIVISION OF ALIGNMENT FUNCTION



SCALE

LASER HEAD/MODULATOR



<u>LASER</u>

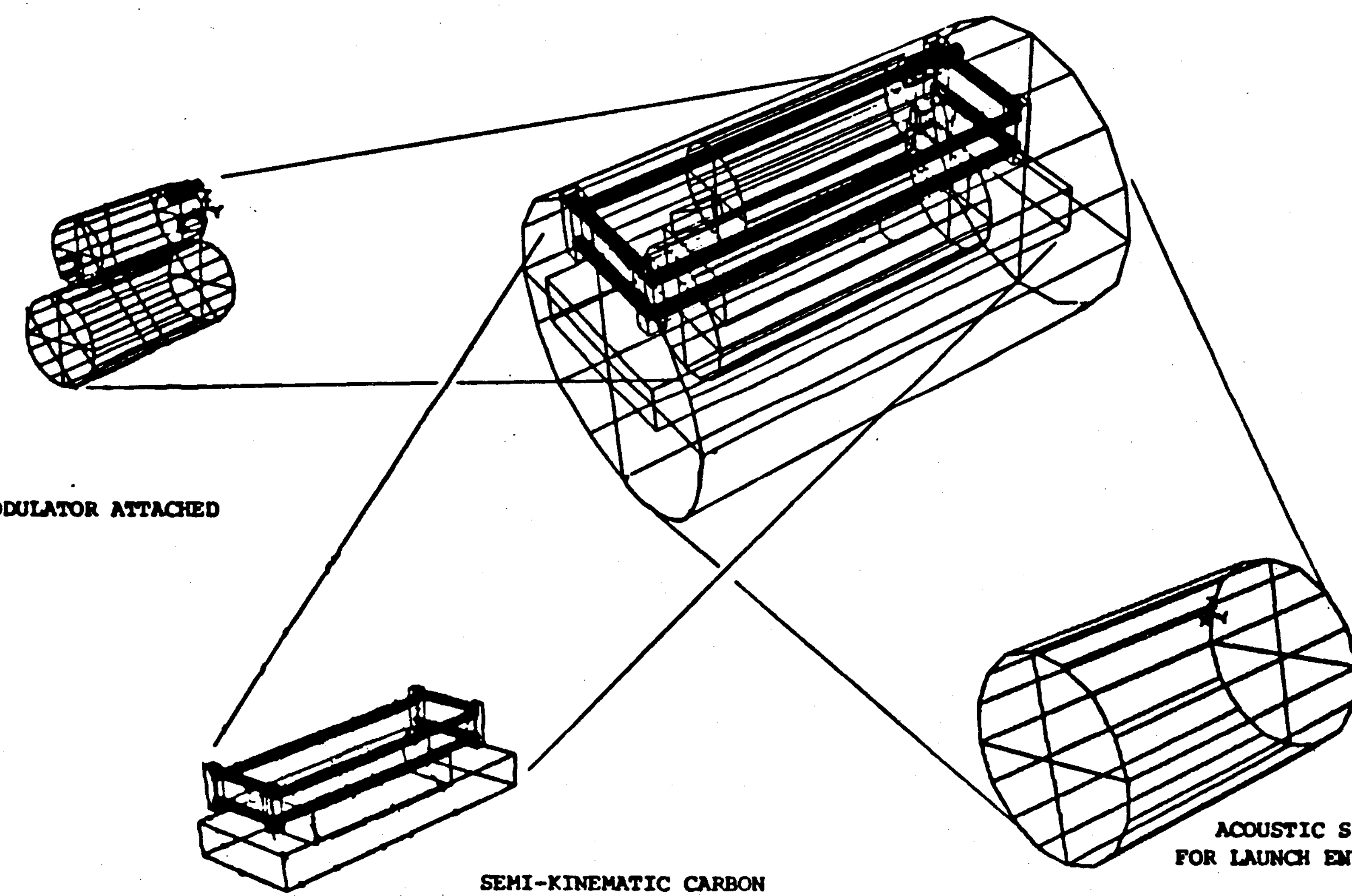
WEIGHT-≈495 lbs
VOLUME-≈4.4 ft^3
(16" dia x 38" lg)

<u>MODULATOR</u>

WEIGHT-≈1000 lbs.
VOLUME-≈8.5 ft^3
(22" dia x 38" lg)

SCALE

STRUCTURAL CONFIGURATION



SCALE

FOR ADDITIONAL DETAILS SEE APPENDIX

SCALE

TELESCOPE

SCALE

SCALE TELESCOPE

- AFOCAL CASSEGRAIN
  DIAMOND TURNED ALUMINUM
  GOLD COATED

PRIMARY DIAMETER	: 125 cm
PRIMARY VERTEX RADIUS	: –400 cm
PRIMARY FIGURE	: PARABOLOID
SECONDARY DIAMETER	: 6.25 cm
SECONDARY VERTEX RADIUS	: –20 cm
SECONDARY FIGURE	: PARABOLOID
PRIMARY – SECONDARY SEPARATION	: 190 cm
SECONDARY MAGNIFICATION	: 20

SURFACE ROUGHNESS $<\frac{\lambda}{5}$ @ 6328 Å

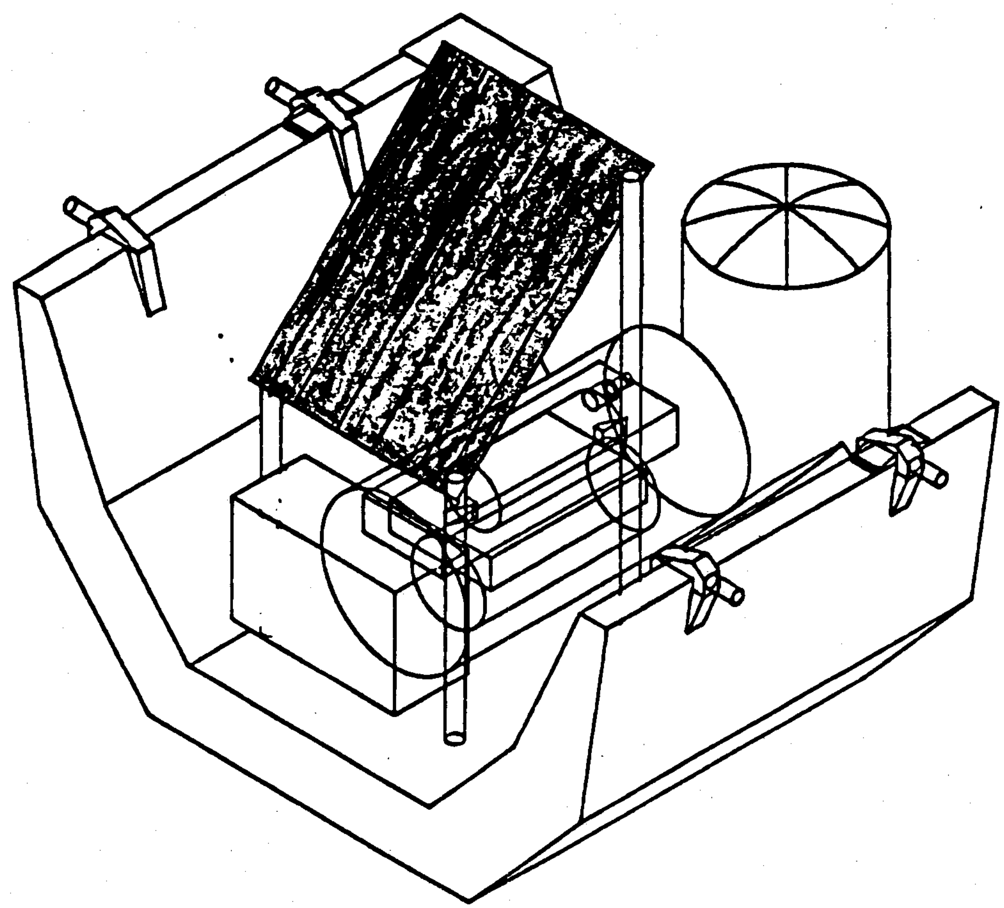
TILT	: 1.9 μ rad DECOLLIMIZATION PER mrad TILT
DECENTER	: 1.9 μ rad DECOLLIMIZATION PER .1 mm DECENTER
DESPACE	: 2.2 μ rad DECOLLIMIZATION PER μm DESPACE

MAXIMUM EXPECTED LAG ANGLE IN OBJECT SPACE	: .11 mrad
MAXIMUM EXPECTED LAG ANGLE IN IMAGE SPACE	: 2.2 mrad

FIXED POINTING

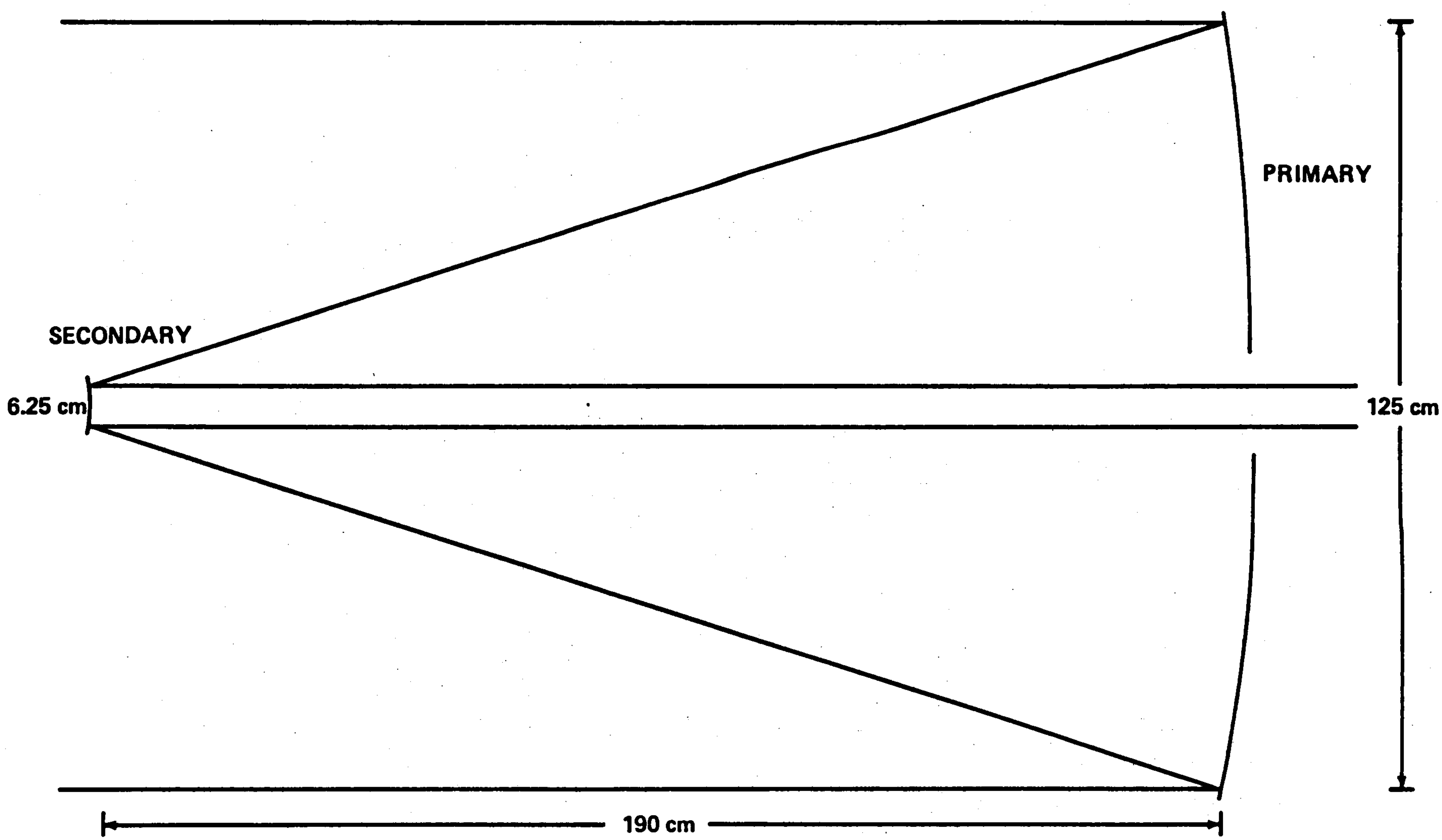
SCALE

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)



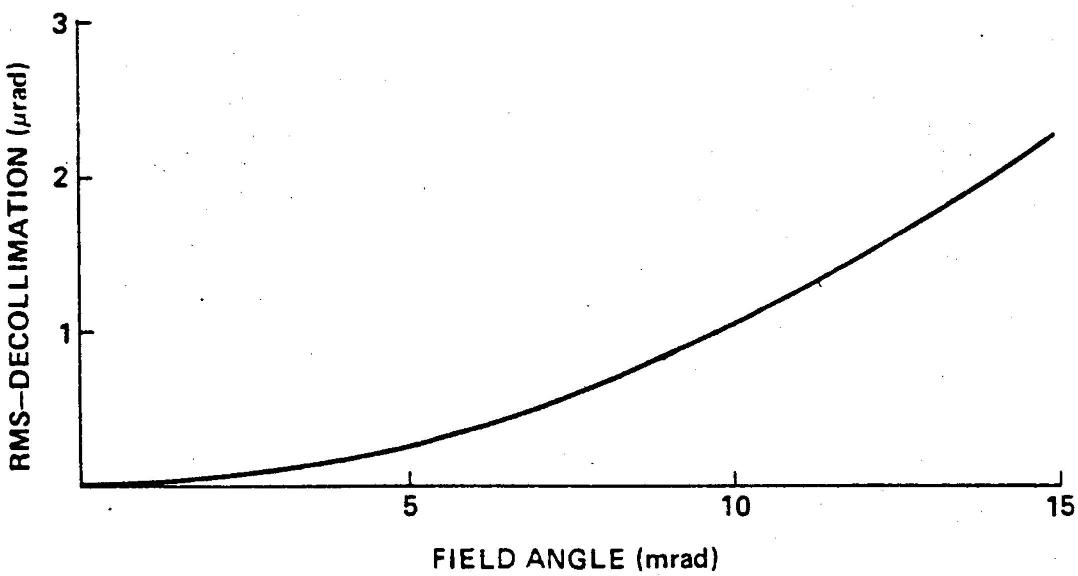
SCALE

SCALE TELESCOPE CONFIGURATION
(AFOCAL CASSEGRAIN)

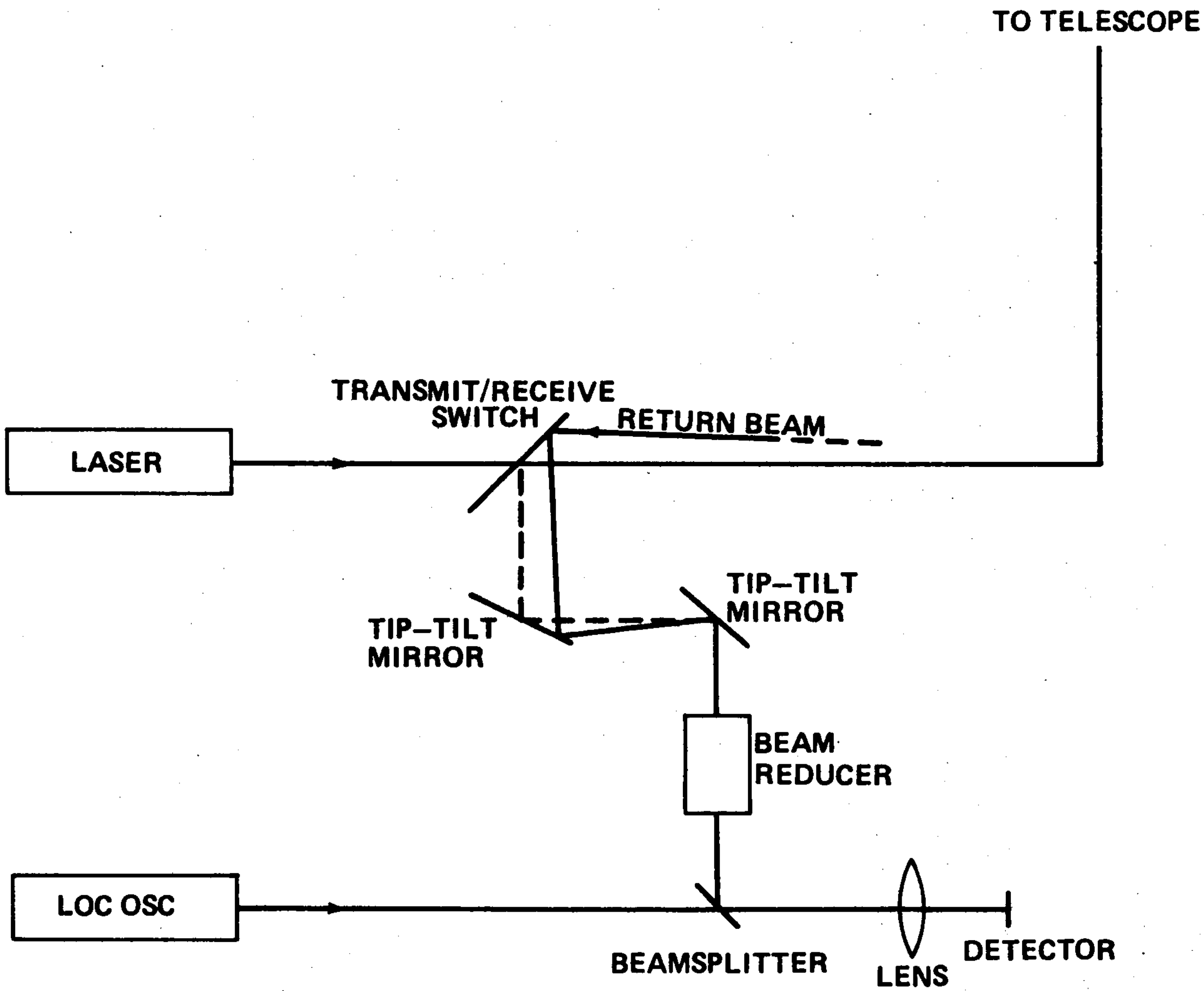


SCALE

SCALE TELESCOPE



SCALE OPTICAL CONFIGURATION



SIGNAL PROCESSING

SCALE

SCALE SIGNAL PROCESSING

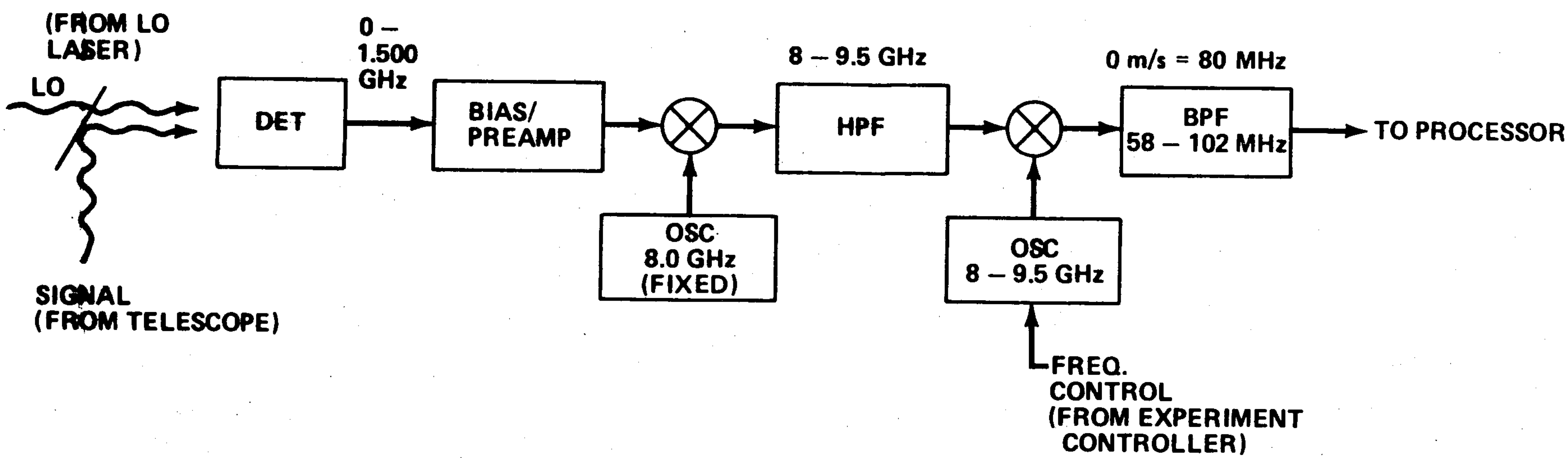
- o GROSS DOPPLER EXTRACTION
- o INPHASE/QUADRATURE DETECTION
- o DYNAMIC RANGE COMPRESSION
- o RAW DATA TRANSFER
- o ON BOARD FFT PROCESSING
- o PROCESSED DATA TRANSFER

SCALE

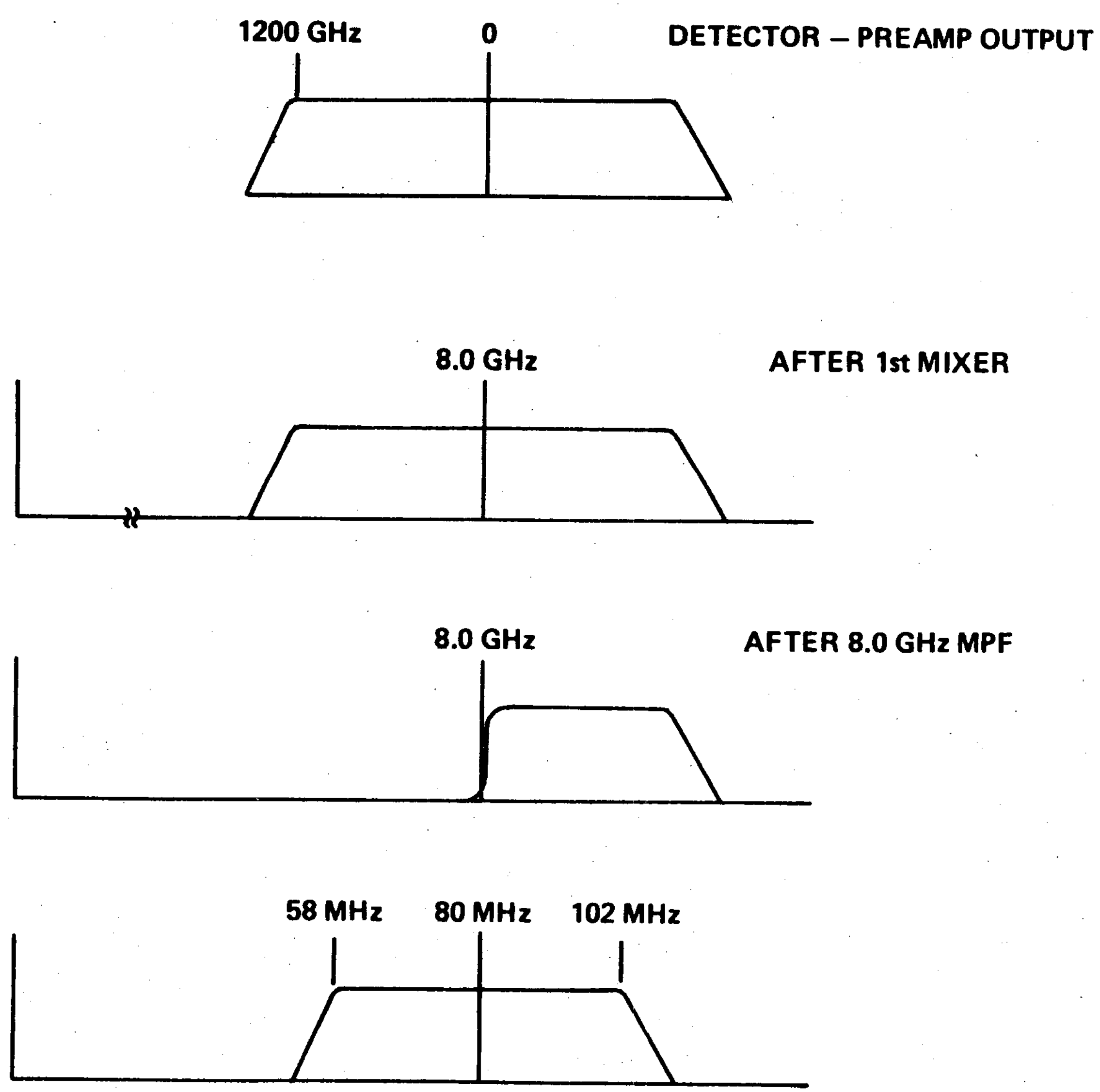
GROSS DOPPLER

- DETECTOR – WIDEBAND, LN_2 – COOLED HgCdTe PHOTO DIODE
- DOUBLE CONVERSION – INPUT SIGNAL UP CONVERTED FROM 0 – 1500 MHz TO 8–9.5 GHz, THEN DOWN CONVERTED TO 80 MHz (NOMINAL) CENTER FREQUENCY
- VCO – TUNED BY EXPERIMENT CONTROLLER, BASED ON
  (1) SHUTTLE INERTIAL RAW DATA
  (2) ON-LINE ANALYSIS OF DOPPLER FREQUENCY OF GROUND ECHOS.

GROSS DOPPLER CORRECTION (RECEIVER)



SCALE


1200 GHz
0
DETECTOR — PREAMP OUTPUT
8.0 GHz
AFTER 1st MIXER
8.0 GHz
AFTER 8.0 GHz MPF
58 MHz
80 MHz
102 MHz

IN—PHASE/QUADRATURE CHANNELS

- 58 – 102 MHz BANDPASS SIGNAL CONVERTED TO 2 0 – 22 MHz BASEBAND SIGNALS – ALLOWS AVAILABLE 44 MHz, 8-BIT ANALOG-TO-DIGITAL CONVERTERS TO BE USED.
- DYNAMIC RANGE COMPRESSION – REQUIRED TO MAINTAIN LINEAR RESPONSE FOR GROUND HITS.

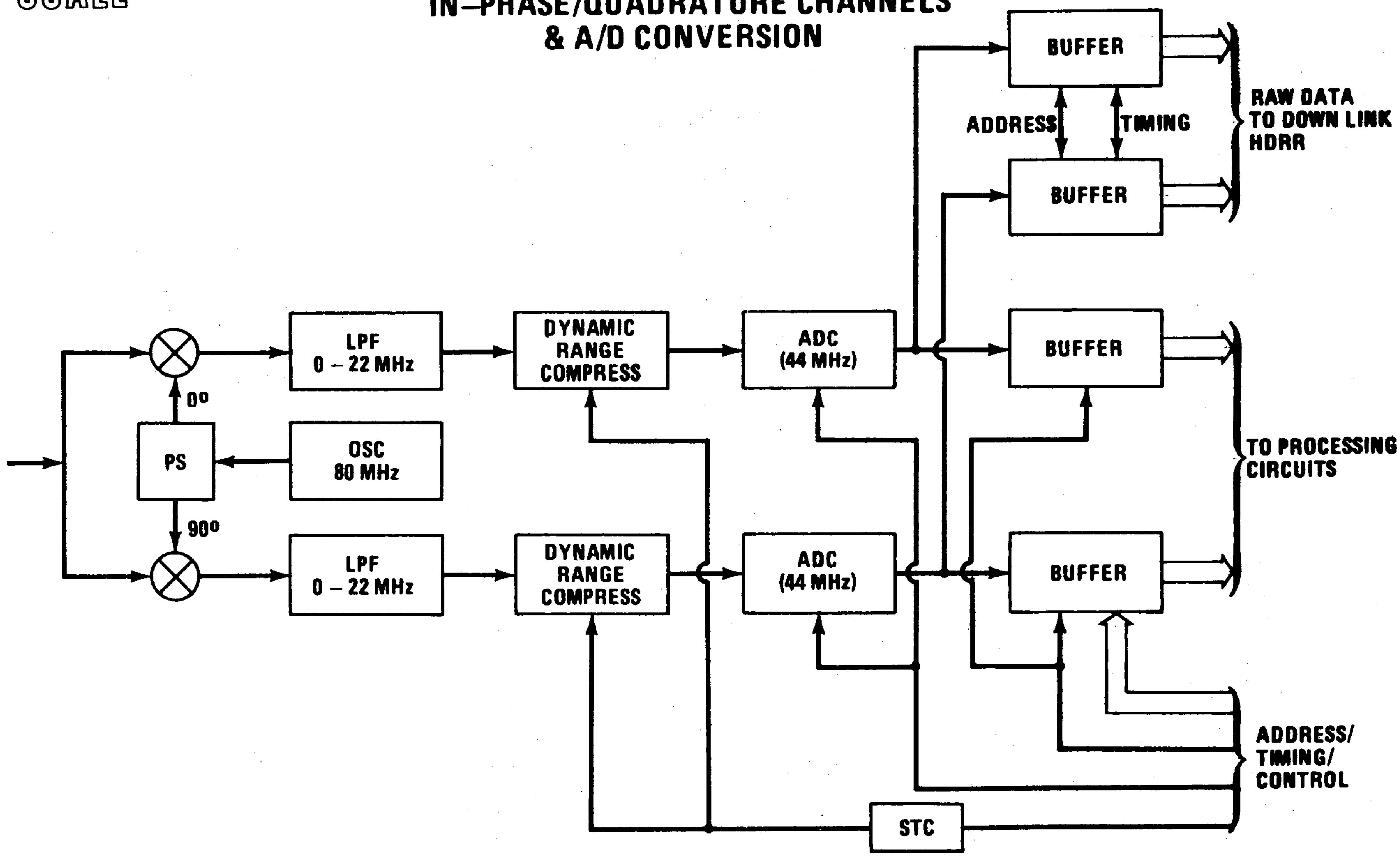
  OPTIONS:
  1. RF LOG COMPRESSION
  2. SENSITIVITY – TIME CONTROL (STC)
  3. DUAL CHANNEL RECEIVER
- DUAL BUFFER DESIGN – ONE PAIR OF BUFFERS HOLDS SIGNAL SAMPLES FOR PROCESSING CIRCUITS. OTHER BUFFER ALLOWS RAW DATA TO BE CLOCKED OUT FOR SHUTTLE/PALLET DATA SYSTEM.

SIGNAL PROCESSING

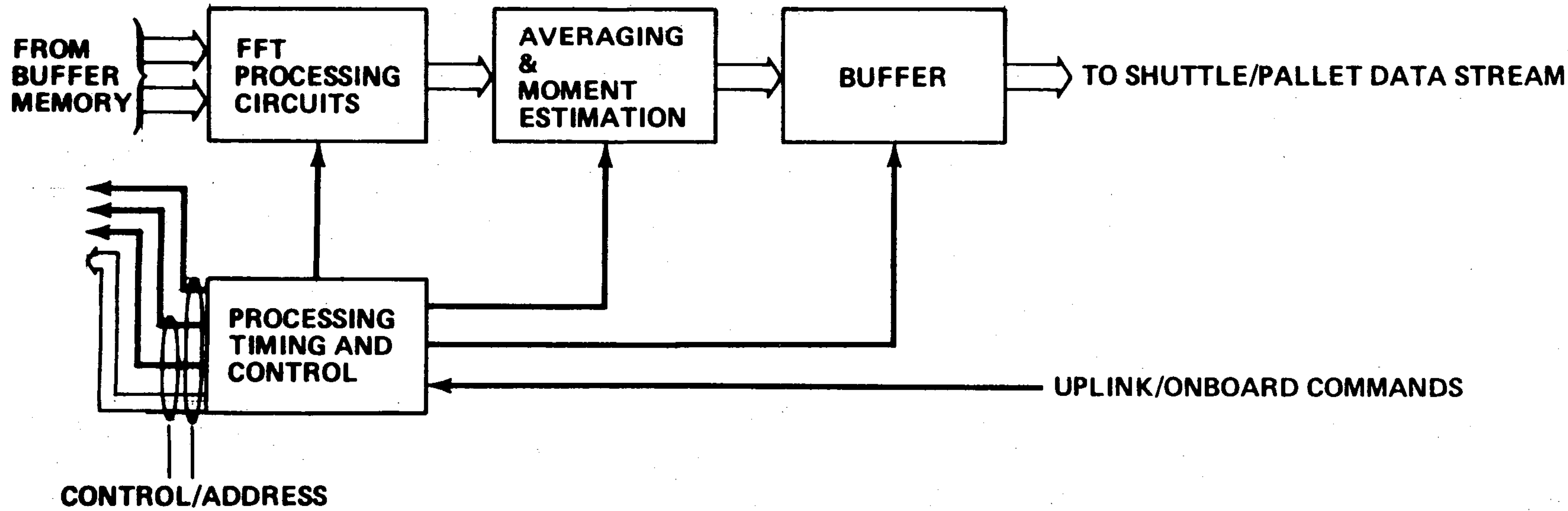
- DIGITIZED SIGNAL IS PROCESSED BY HARDWARE REALIZATION OF FAST FOURIER TRANSFORM (FFT) ALGORITHM.
- MULTIPLE PULSE AVERAGING AND MOMENT ESTIMATION IS DONE ON OUTPUT OF FFT HARDWARE.
- MOMENTS (3/RANGE BIN) ARE BUFFERED AND CLOCKED OUT TO PALLET/SHUTTLE DATA STREAM.

SCALE

IN–PHASE/QUADRATURE CHANNELS & A/D CONVERSION



SIGNAL PROCESSING



SCALE

SCALE ACCOMMODATION STUDY

SCALE

SHUTTLE ACCOMMODATIONS

- USE EXISTING LASER DESIGN
- FIXED POINTING TELESCOPE
- SPACELAB EXPERIMENT

SCALE

ORBITAL ANALYSIS

SCALE

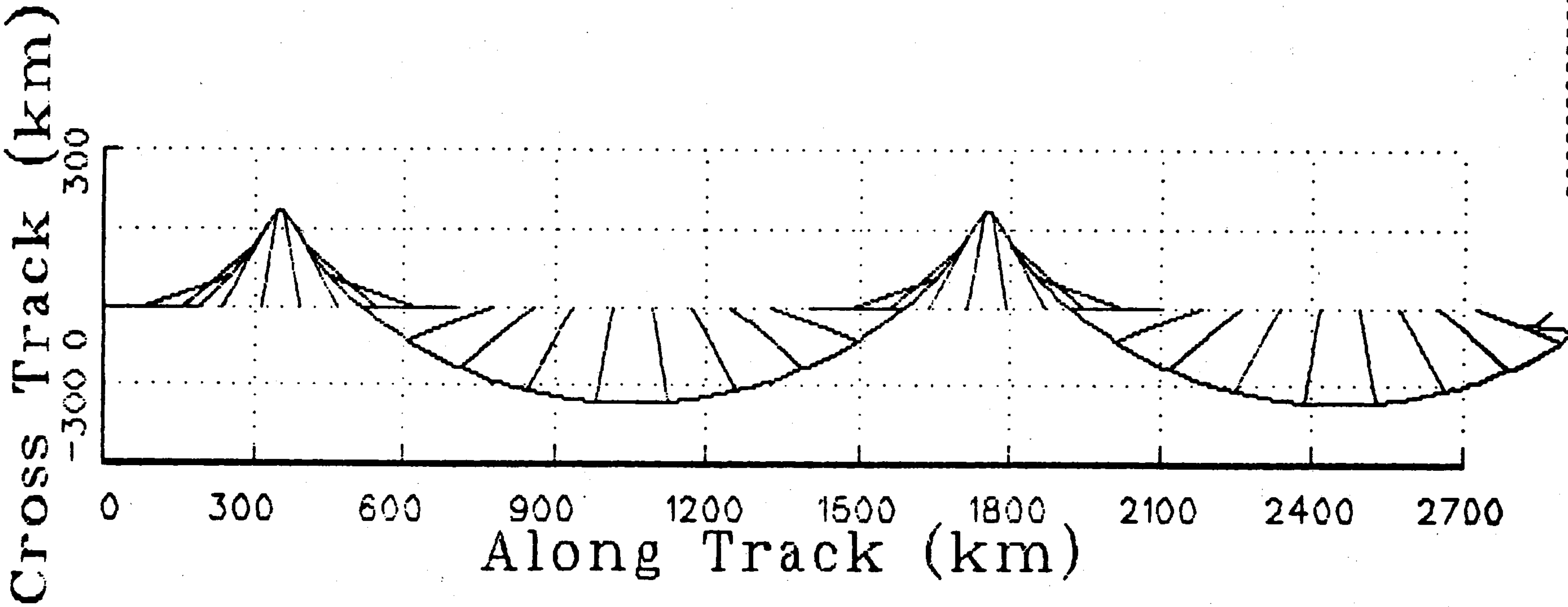
THE FOLLOWING TWO FIGURES SHOW THE GROUND TRACK OF THE LIDAR AS IT ROTATES. THE LIDAR TELESCOPE IS TILTED 45 DEGREES FROM THE VERTICAL AND ROTATES AT A RATE OF 2.0 DEGREES PER SECOND ABOUT THE YAW (Z) AXIS. THE SHUTTLE ORBIT ALTITUDE IS APPROXIMATELY 185 KILOMETERS.

THE FIRST FIGURE SHOWS THE GROUND TRACK FOR TWO COMPLETE ROTATIONS OF THE LIDAR, WHICH COVERS A DISTANCE OF 3,000 KILOMETERS ON THE EARTH'S SURFACE. THE STRAIGHT LINES FROM THE CENTER OF THE GROUND TRACK SHOW THE POSITION OF THE SHUTTLE AND THE DIRECTION THAT THE LIDAR IS POINTED.

THE SECOND FIGURE SHOWS THE GROUND TRACK OF THE LIDAR AS THE SHUTTLE PASSES OVER A TARGET, IN THIS CASE, HUNTSVILLE, ALABAMA. THE CIRCLE REPRESENTS A 150 KILOMETER RADIUS AROUND HUNTSVILLE.

SCALE

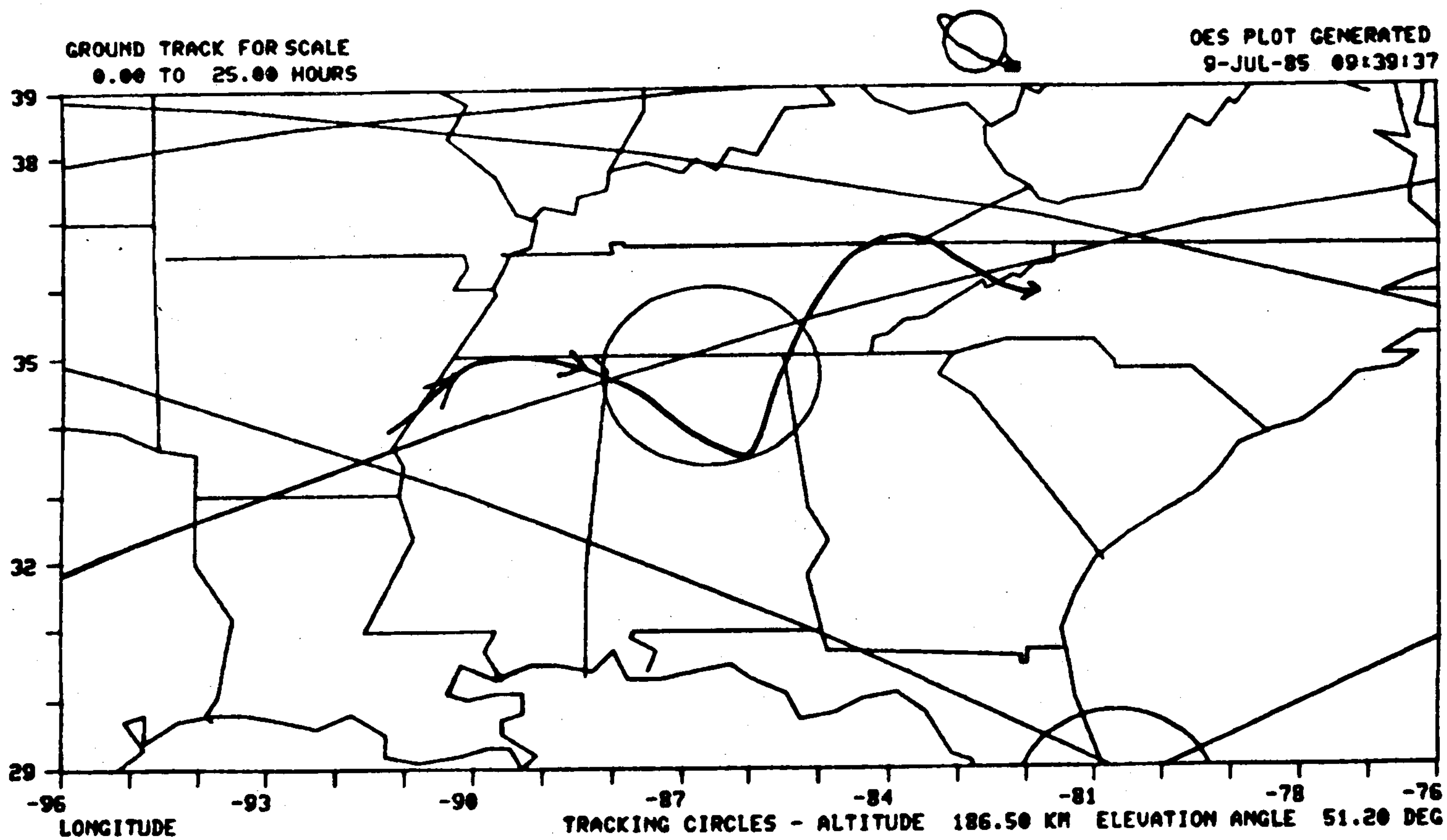
LIDAR GROUND HITS



45 degrees, 185 km, 2.0 deg/sec
7.8 km/sec

SCALE

LIDAR GROUND HITS



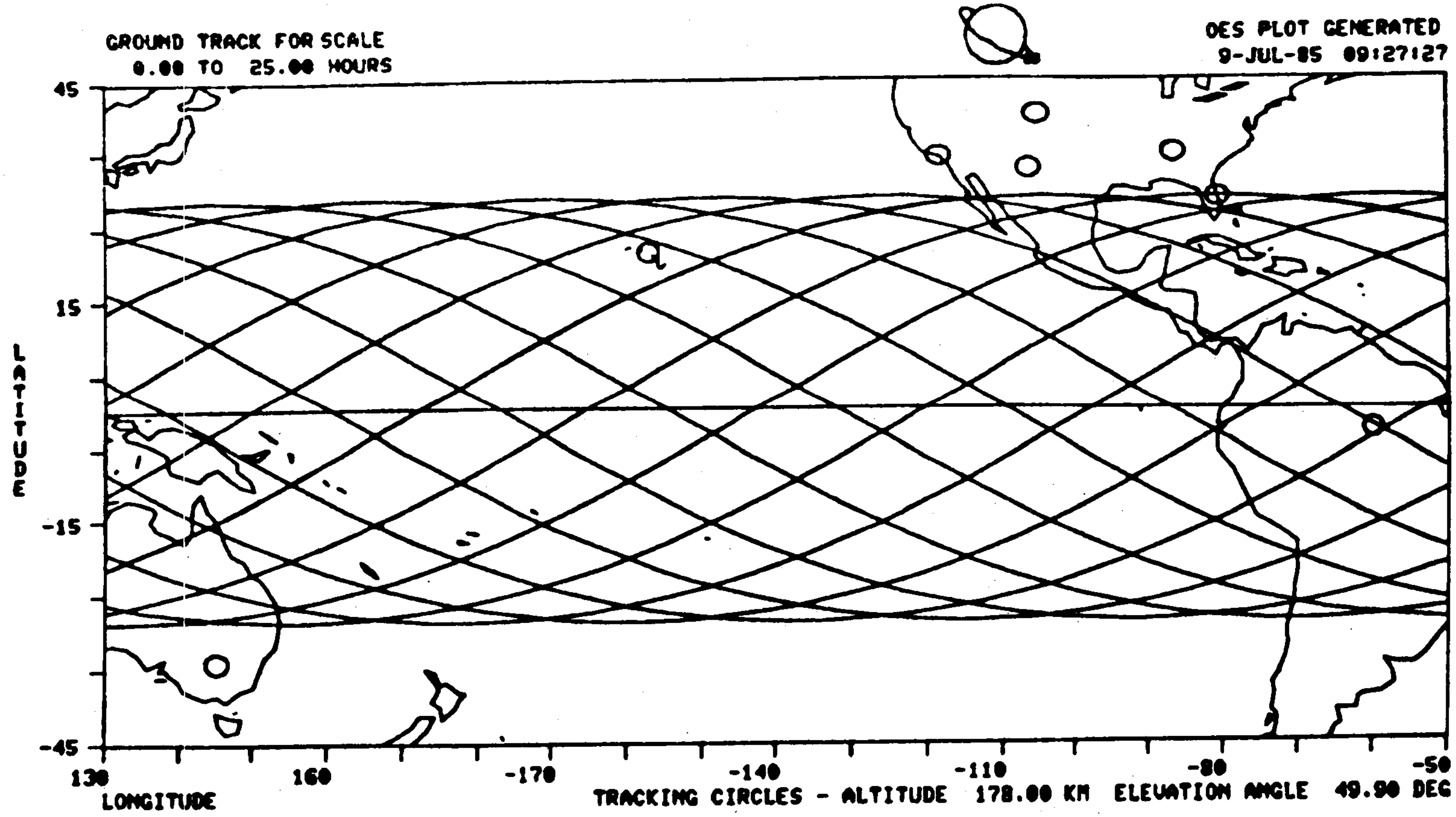
ENTER OPTION OR TYPE HELP)

SCALE

THE FOLLOWING THREE FIGURES SHOW THE GROUND TRACK FOR A 24 HOUR REPEATING ORBIT FOR ORBIT INCLINATIONS OF 28.5, 35 AND 40 DEGREES RESPECTIVELY. THE SMALL CIRCLES REPRESENT AREAS OF 150 KILOMETER RADIUS AROUND 8 PROPOSED LIDAR GROUND-TRUTH SITES.

BELOW EACH FIGURE IS LISTED THE ORBIT ALTITUDE REQUIRED TO OBTAIN A 24 HOUR REPEATING ORBIT FOR THE INDICATED ORBIT INCLINATION, AND THE GROUND TARGETS THAT ARE CROSSED BY THE ORBIT PATH.

SCALE



24 HOUR REPEATING ORBIT

INCLINATION 28.5 DEG

ALTITUDE 178 KM

TARGETS AVAILABLE (SHOWN BY - O)

	SITE	LATITUDE	LONGITUDE
	BOULDER, CO	40.0	-156.26
	HUNTSVILLE, AL	34.7	-86.6
✓	KSC, FL	28.5	-80.7
✓	MANAUS, BRAZIL	-3.06	-60.0
✓	MAUNA LOA, HA	21.2	-157.2
	MELBOURNE, AUSTRALIA	-34.2	145.0
	PASADENA, CA	34.1	-118.52
	WHITE SANDS, NM	32,4	-106.5

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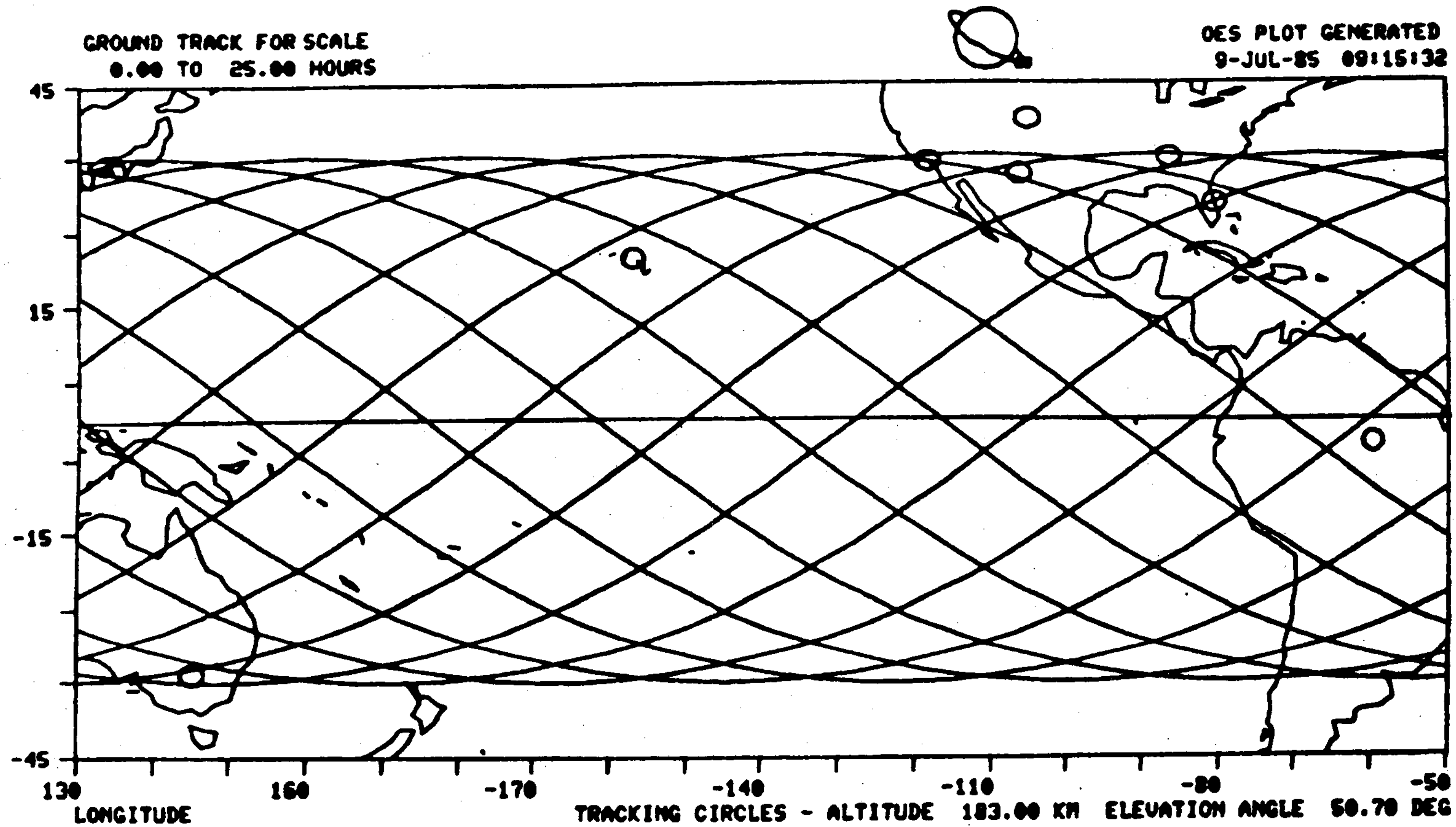
SCALE



24 HOUR REPEATING ORBIT

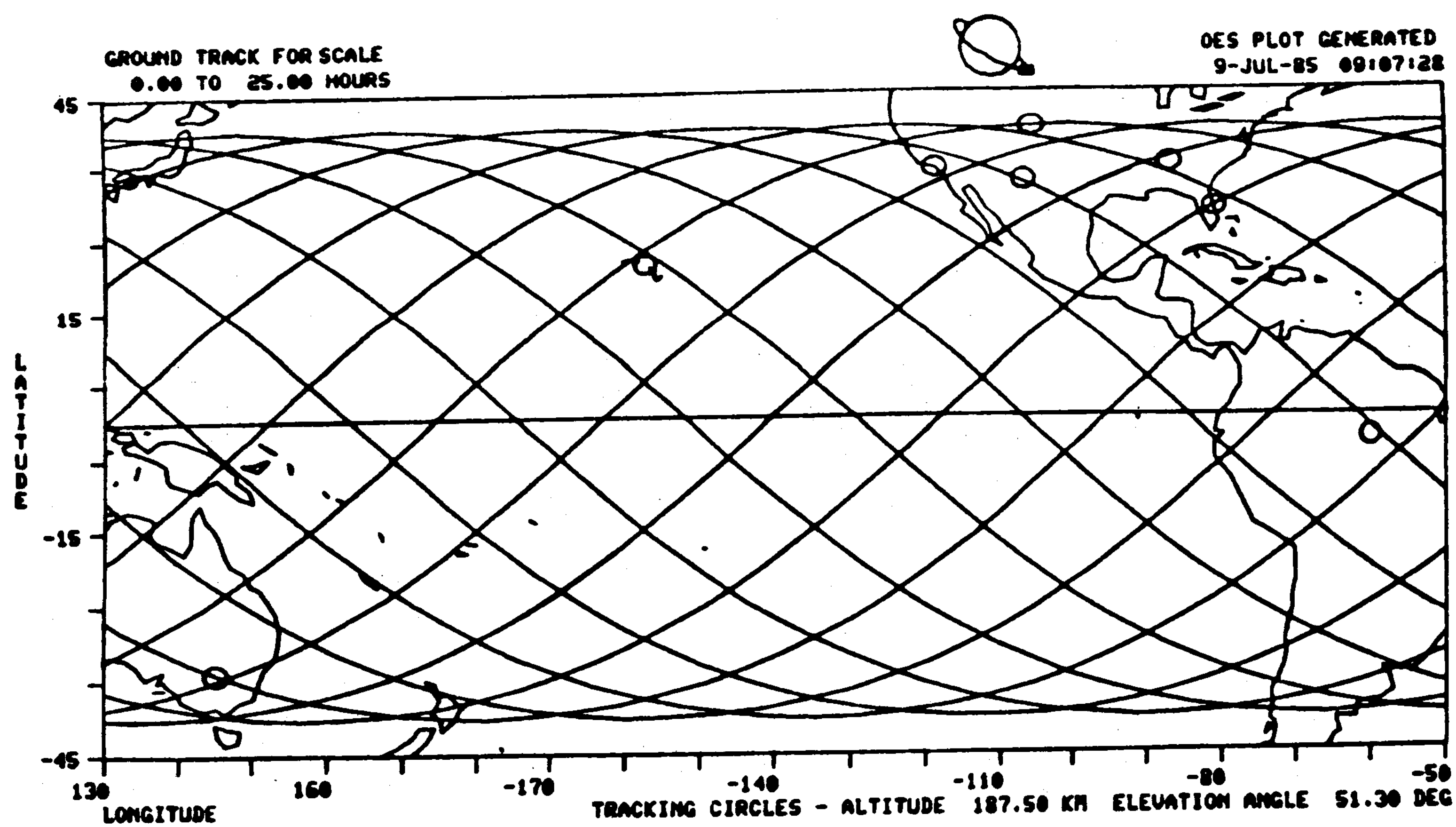
INCLINATION 35 DEG

ALTITUDE 183 KM

TARGETS AVAILABLE (SHOWN BY - O)

	SITE	LATITUDE	LONGITUDE
	BOULDER, CO	40.0	-156.26
✓	HUNTSVILLE, AL	34.7	-86.6
✓	KSC, FL	28.5	-80.7
	MANAUS, BRAZIL	-3.06	-60.0
	MAUNA LOA, HA	21.2	-157.2
✓	MELBOURNE, AUSTRALIA	-34.2	145.0
✓	PASADENA, CA	34.1	-118.52
✓	WHITE SANDS, NM	32,4	-106.5

SCALE



24 HOUR REPEATING ORBIT

INCLINATION 40 DEG

ALTITUDE 187.5 KM

TARGETS AVAILABLE (SHOWN BY - O)

	SITE	LATITUDE	LONGITUDE
✓	BOULDER, CO	40.0	-156.26
✓	HUNTSVILLE, AL	34.7	-86.6
✓	KSC, FL	28.5	-80.7
✓	MANAUS, BRAZIL	-3.06	-60.0
✓	MAUNA LOA, HA	21.2	-157.2
✓	MELBOURNE, AUSTRALIA	-34.2	145.0
	PASADENA, CA	34.1	-118.52
✓	WHITE SANDS, NM	32,4	-106.5

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SCALE

POINTING AND CONTROL

SCALE

POINTING AND CONTROL FOR SCALE

1. Options for pointing of LIDAR
2. Guidelines using yaw maneuver
3. Orbiter pointing
4. Orbiter control modes
5. Pointing error
6. Propellant usage
7. Summary

PD12/J. FIKES

SCALE

OPTIONS FOR POINTING OF LIDAR

- O POINTING USING THE ORBITER
  - ORBITER IN PITCH MOVEMENT ABOUT NADIR (PITCH)
  - ORBITER MOVING IN CIRCULAR PATH ABOUT NADIR (YAW)
- O POINTING USING A GIMBALED MIRROR
- O POINTING USING IPS

SCALE

OPTIONS FOR POINTING OF LIDAR

There are several different options that can be utilized to achieve the requirements for pointing of the LIDAR experiment. The scientific requirements are to point the LIDAR at one place from some angle and then point at the same place again from a different angle. This allows the measurement of the wind speed to be made from the doppler shift using vector analysis.

There are certain places on Earth where these measurements need to be made. So the science group requires that the pointing at a certain place on Earth from two different angles occur twice during each orbit. This can be accomplished by using several different options which are listed on the facing page.

While all of these options will accomplish the requirements, pointing using the Orbiter is the preferred case. This option will minimize the complexity of the experiment and keep down cost. The case of the Orbiter moving in a circular path about the local vertical was chosen from the options to minimize both the air support equipment and Orbiter propellant requirements.

The Orbiter moving in the yaw direction at 2^{o}/sec with the telescope mounted at a 45^{o} angle from nadir will produce a ground track that overlaps and gives a point on Earth from two different angles. This gives the science group good data for calculating the wind velocity.

SCALE

GUIDELINES FOR SCALE POINTING USING YAW MANEUVER OPTION

- MANEUVER THE ORBITER IN A CIRCULAR PATH ABOUT LOCAL VERTICAL
- 100 N.MI. ALTITUDE
- 2°/SEC MANEUVER RATE
- 2 MANEUVERS PER ORBIT
- EXPERIMENT IS OPERATIONAL FOR 5 HOURS A DAY
- MISSION IS 7 DAYS
- 47 MANEUVERS DURING MISSION

GUIDELINES FOR SCALE POINTING USING YAW MANEUVER OPTION

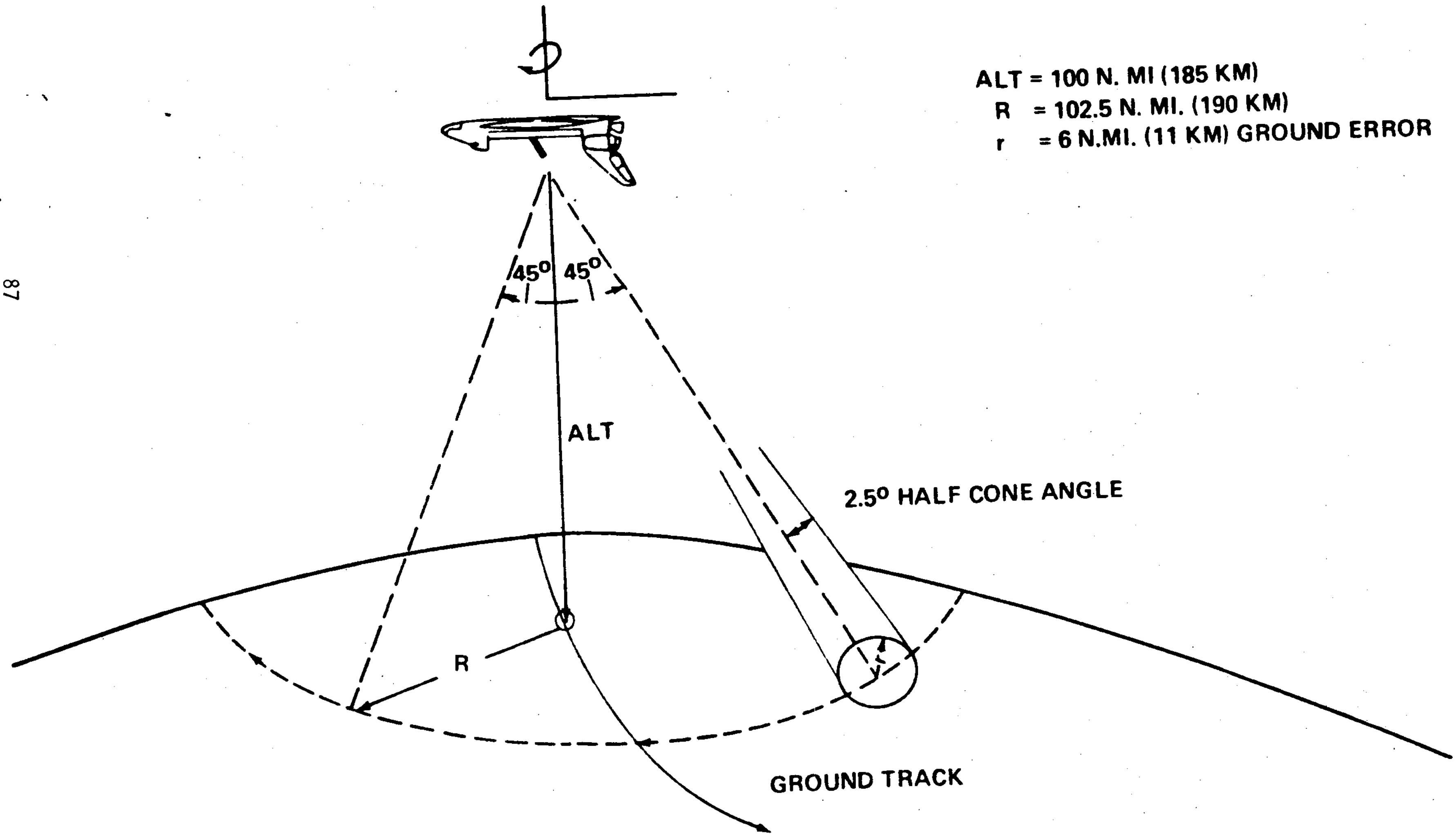
There are several guidelines that were followed in doing this study. These are shown on the facing page. The Orbiter is maneuvered in a circular path about the local vertical at 2°/sec. This rate is needed to get an overlap in the ground track so a place on Earth is pointed at from different angles.

For this experiment the lowest possible altitude that could be achieved and maintained by the Orbiter was desirable. This would give more accurate and useful data. The altitude of 100 n.mi. is the lower limit that the Orbiter can maintain and thus will be used in this study.

The total mission time is 7 days, which is the normal Orbiter flight duration. During this time, the experiment will operate for 5 hours each day. The yaw maneuver will be made twice per orbit and a total of 47 times during the mission. It will take 3 minutes to complete each maneuver and the maneuver time will be 6 minutes per orbit. When the Orbiter is not performing the maneuver, it will be flying along with the cargo bay toward Earth and in a minimum energy state.

SCALE
3546–85

ORBITER POINTING



ORBITER POINTING

The Orbiter is maneuvering about the local vertical at a rate of 2°/sec. The telescope is mounted 45° off local vertical as shown on the facing page. The distance from local vertical to the point where the LIDAR hits the Earth is 190 km.

From an altitude of 185 km and with a 2.5° half cone angle error, the ground error seen on Earth is ± 11 km. This represents the maximum error that will be seen. The error is due to several different reasons, which will be talked about later.

When the Orbiter is doing the yaw maneuver, it is placed in a manual mode. A deadband of ± 0.5° and a stability rate of 0.2°/sec can be achieved in manual mode for a maneuver rate of 2°/sec. JSC did a simulation of the Orbiter for this case to verify the performance. More will be said about this and about the different modes of operation later.

The Orbiter will be flying along with the cargo bay toward Earth in an aircraft orientation for the period when the Orbiter is not performing the yaw maneuver During this period, the deadband will be ± 0.1°, thus reducing the maximum half cone angle error to 2.1°. This represents a maximum ground error of ± 9.6 km when in an aircraft orientation.

SCALE

ORBITER CONTROL MODES FOR SCALE

- o AUTOMATIC MODE
  - o AUTOMATIC ATTITUDE HOLD FOR ALL THREE AXIS
  - o HOLDS THREE AXIS TO THE DEADBAND (0.1°)
- o MANUAL MODE
  - o DISCRETE MODE
    - HOLDS TWO AXIS TO THE DEADBAND (0.1°)
    - USES VERNIER THRUSTERS
  - o ACCELERATION MODE
    - ACCELERATES MANEUVER IN YAW DIRECTION
    - USES PRIMARY THRUSTERS
    - Y-AXIS IN FREE DRIFT
  - o PULSE MODE
    - PULSES MANEUVER IN YAW DIRECTION
    - USES PRIMARY THRUSTERS
    - Y-AXIS IN FREE DRIFT

ORBITER CONTROL MODES FOR SCALE

There are several different modes of operation for the Orbiter as illustrated on the facing page. The two main modes of operation are the automatic mode and the manual mode.

The automatic mode holds all three axes to a deadband of 0.1° automatically. While not doing the yaw maneuver the Orbiter will operate in this mode. This will be the case for the majority of the experiment.

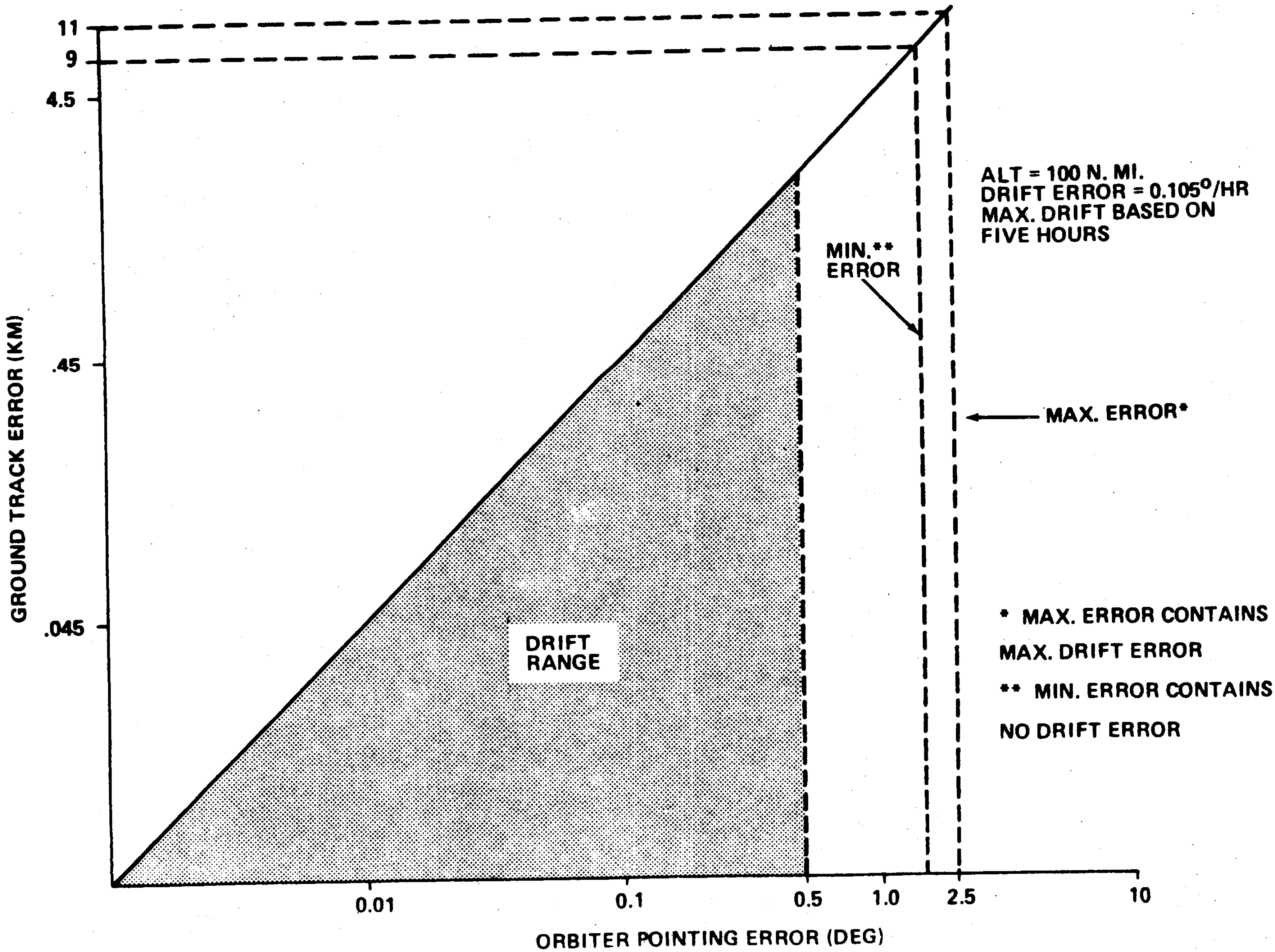
During the yaw maneuver, which accounts for 6 minutes per orbit, the Orbiter will operate in the manual mode. There exists three different sub-modes in manual mode operation. They are discrete mode, acceleration mode and pulse mode.

To get the 2°/sec maneuver rate, the Orbiter has to operate in either the acceleration or pulse mode. Both use the 870 lb primary thrusters to accomplish this rotation. In the acceleration mode, the thrusters accelerate the Orbiter to approximately the intended rate, then stops and checks to make sure the desired rate was achieved. In the pulse mode, thrusters pulse up the rate until the desired rate is acheived.

After the rate is achieved, the Orbiter is switched into discrete mode to hold it constant. Vernier thrusters are usually used during this mode, but for a rate of 2°/sec they are not adequate. The simulation done by JSC showed that the primary thrusters had to be used, which made the deadband grow to 0.5°.

SCALE 3545–85

POINTING ERROR



POINTING ERROR

The maximum pointing error is 2.5°. There are several factors that are involved in this total error. First there is a 0.5° error present at the Orbiter IMU. From the IMU to the payload there is an additional 1° error. Due to the Orbiter operating in manual mode there is a deadband error of 0.5°. This is a total of a 2° error which represents the minimum error that can be achieved.

The IMU drift also has to be taken into account. The drift error is 0.105°/hr, which is 0.5° for the 5 hours the experiment is on. So the error varies from 2° to 2.5°, according to the time.

For the minimum error of 2° there is a ground track error of 9 km as seen on the facing page. For the maximum error, which includes all the drift error for 5 hours, the ground track error is going to be 11 km. Therefore, the ground track error is going to be between 9 and 11 km which is adequate for the experiment.

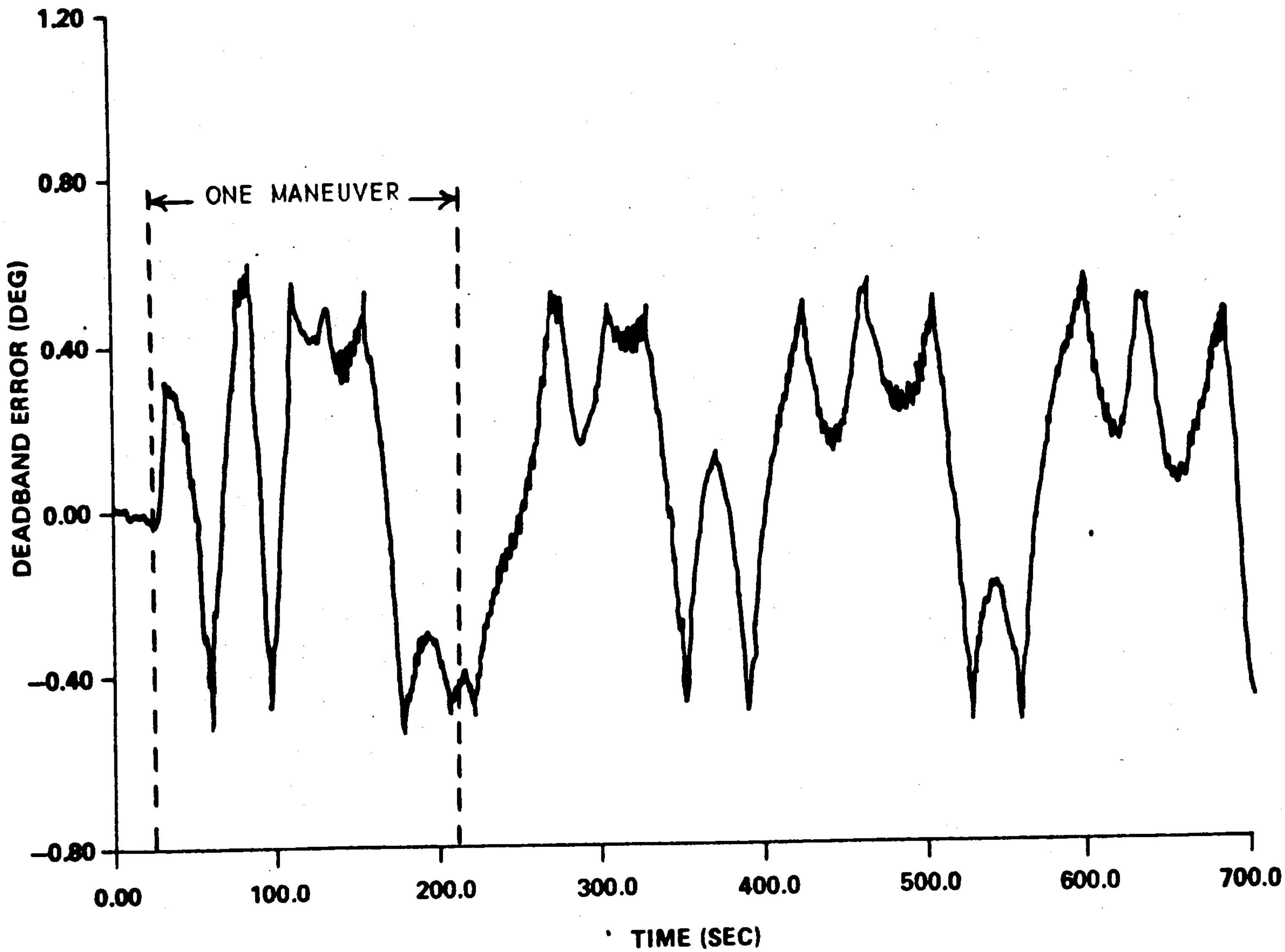
The error talked about above is when the Orbiter is conducting the yaw maneuver. The period when the Orbiter is just flying along the deadband decreases to 0.1°. This gives a maximum error of 2.1° and a minimum error of 1.6° depending on the drift time. The case when the Orbiter is in the yaw maneuver has the worse error, so the pointing accuracy is going to be adequate for both cases.

The errors were assumed to be linear. They were added together to get the total error, which represents the worse case. If this assumption wasn't made, the RSS value of the 3σ errors would be used. The Orbiter IMU error (0.5°) and error between the IMU and payload (1°) are 3σ errors. Taking the RSS of these two errors and adding this value to the other errors, the maximum error is 2.1° and the minimum error is 1.6°. For the period when the Orbiter is not in the yaw maneuver, the maximum error is 1.7° and the minimum error is 1.2°. This is considering the use of RSS.

4363-85

SCALE

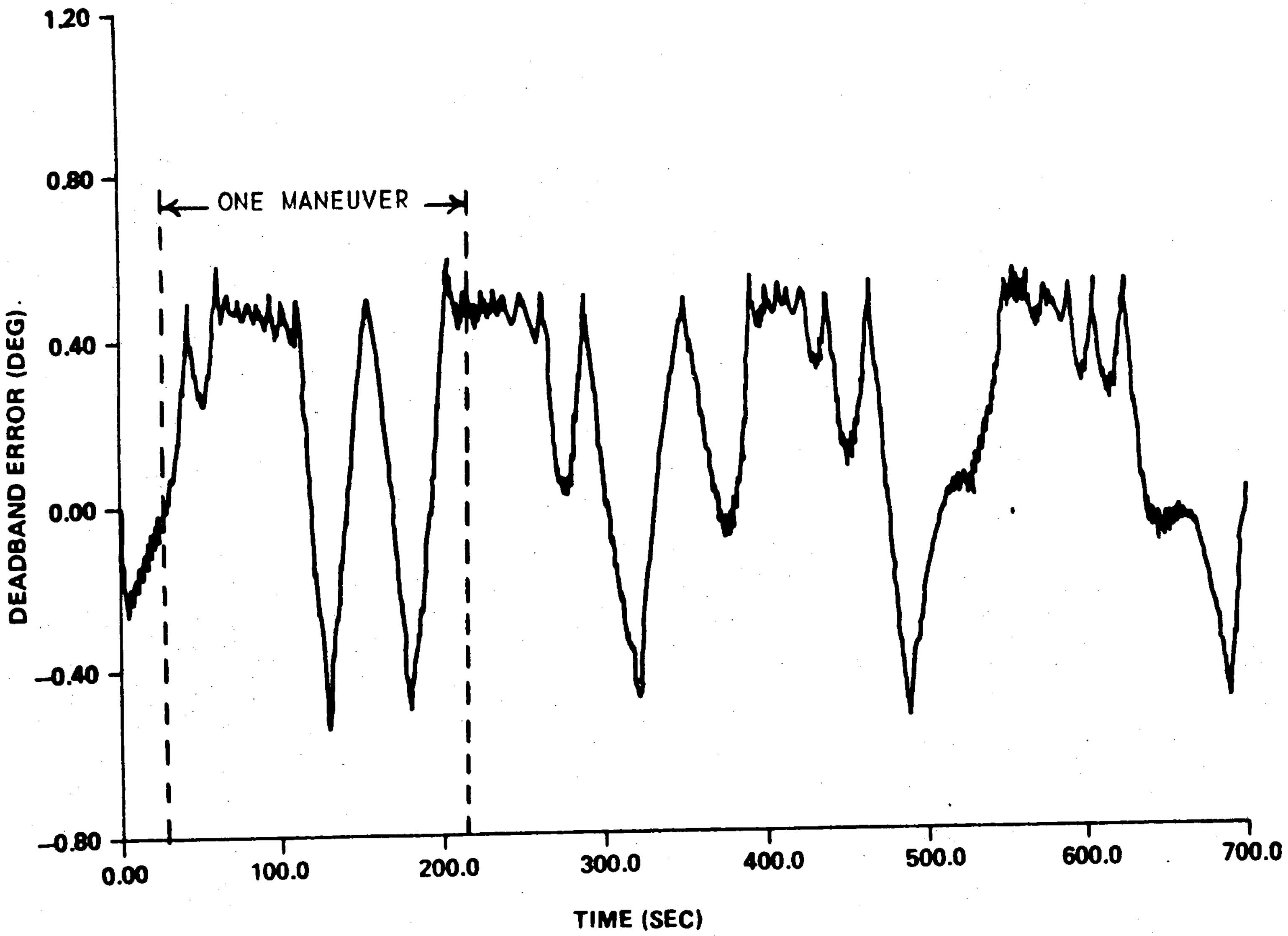
ORBITER X–AXIS DEADBAND ERROR



4354-85

SCALE

ORBITER Y–AXIS DEADBAND ERROR

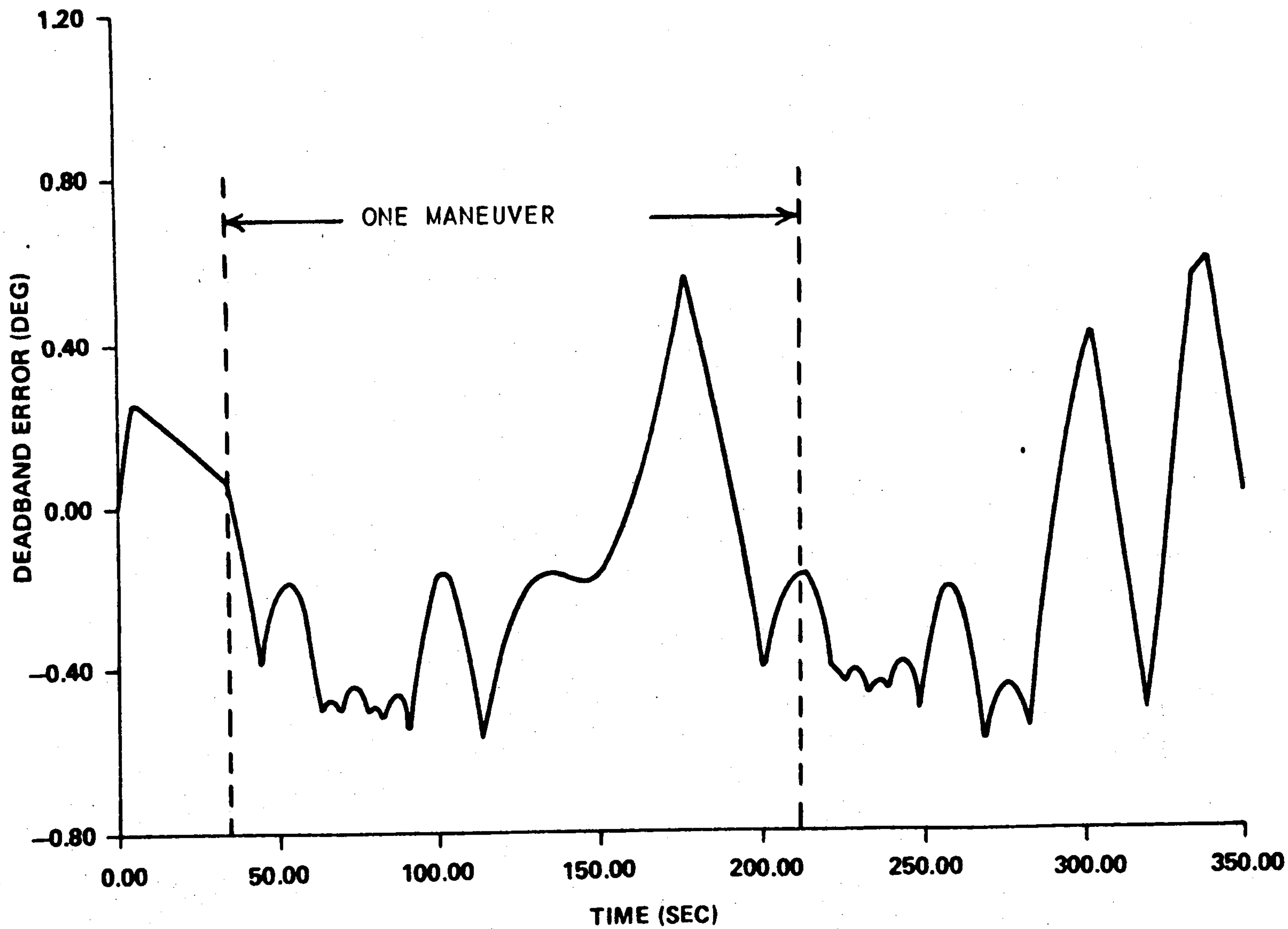


4352-85

SCALE

C-2

SCALE LOS DEADBAND ERROR



SCALE

ORBITER DEADBAND ERROR

The simulation performed by JSC (Lockheed) verified that the deadband error is approximately $\pm 0.5^\circ$. The plots on the next three pages show the deadband error for the Orbiter x-axis, the Orbiter y-axis and the LOS axis 45° off nadir.

The dashed lines show where a maneuver starts and stops. There were about 70 thruster firings from the primary thrusters to maintain the $\pm 0.5^\circ$ deadband during one complete maneuver. These firings can be seen by the heavy lines on the x-axis plot and y-axis plot.

SCALE

PROPELLANT USAGE (RCS)

- 23.5 lbs of propellant per maneuver from forward tank
- 27.5 lbs of propellant per maneuver from aft tank
- 0.7 lbs/hour of propellant for attitude hold
- Total propellant required from the forward tank for the mission is 1117 lbs
- Total propellant required from the aft tank for the mission is 1305 lbs
- Total propellant available for on-orbit use from forward tank is 1700 lbs[2]
- Total propellant available for on-orbit use from aft tank is 1400 lbs[1, 2]
- Total capacity of the forward tank is 2418 lbs
- Total capacity of the aft tank is 4826 lbs[1]

1 2000 lbs of propellant can be obtained from OMS tank.

2 Shuttle systems weight and performance monthly status report Feb. 1, 1982

PROPELLANT USAGE (RCS)

One of the major concerns with doing this yaw maneuver is propellant consumption. The maneuver will be conducted by the use of the primary thrusters. The RCS propellant capacity of the forward and aft tanks will be the limiting factor. The numbers are shown on the facing page.

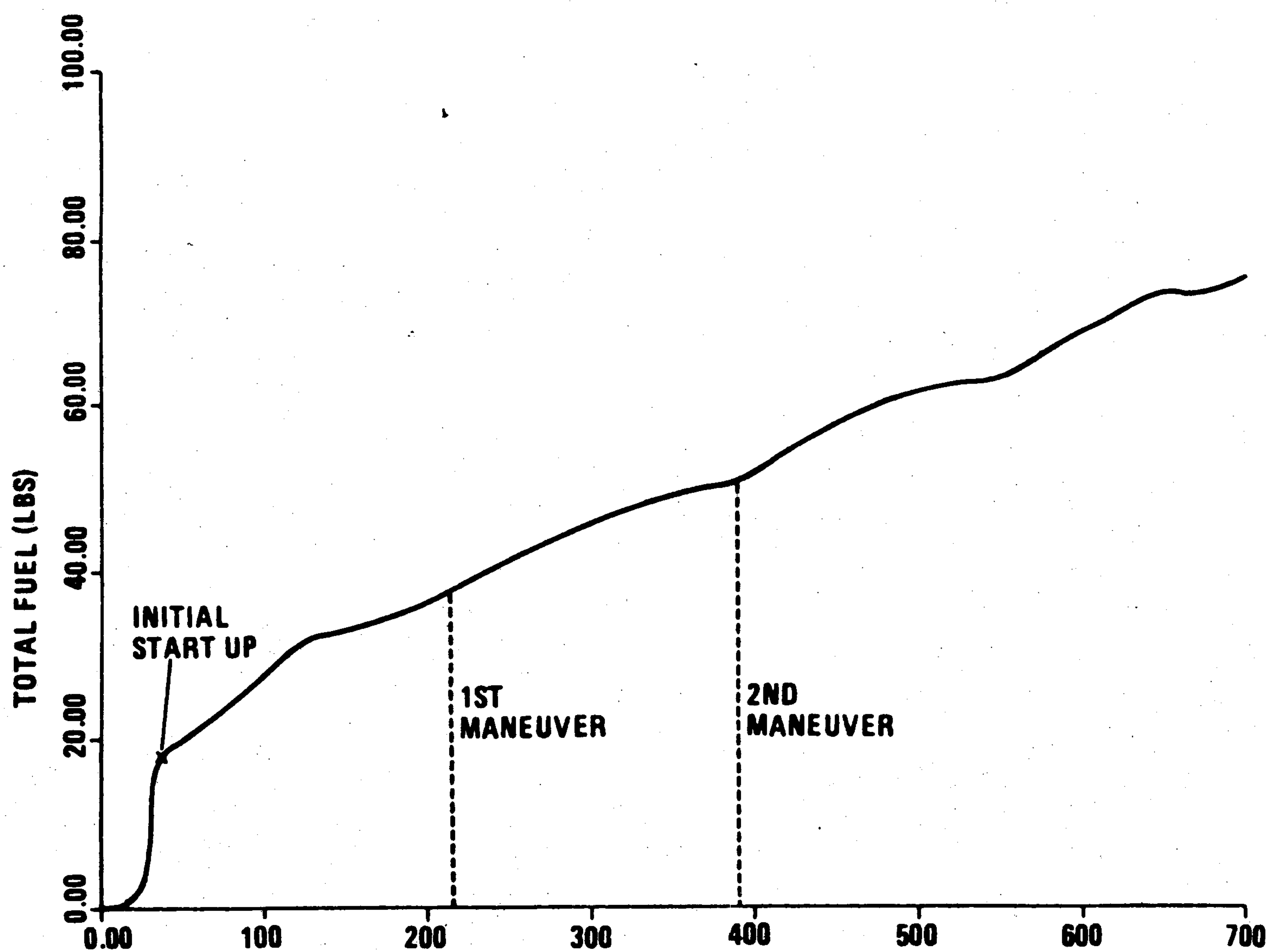
For the forward tank the total capacity is 2418 lbs, with 1700 lbs of this propellant available for on-orbit use. The total capacity of the aft tank is 4836 lbs, plus 2000 lbs available from the OMS tank if needed. For on-orbit use the propellant available from the aft tank is 1400 lbs plus part or all of the 2000 extra pounds.

JSC conducted a simulation to determine if the 2^{o}/sec yaw maneuver is feasible. It showed that the primary thrusters could do this maneuver and hold to a $\pm 0.5^{o}$ deadband. The amount of propellant used for one maneuver was determined to be 23.5 lbs from the forward tank and 27.5 lbs from the aft tank. From this the total amount of propellant used for the experiment during the entire mission is 1117 lbs from the forward tank and 1305 lbs from the aft tank.

After subtracting the amount of propellant used by this experiment there will be 583 lbs in the forward and 95 lbs in the aft tanks available for on-orbit use by other payloads. There is also an additional 2000 lbs of propellant that could be added to the aft tank.

4153–85
SCALE

PROPELLANT CONSUMPTION



SSFS 070285 TIME (SEC)

* CHART IS FROM A SIMULATION BY JSC (LOCKHEED)

PROPELLANT CONSUMPTION

The propellant consumption is shown on the facing page. This chart is a plot from the simulation run by Lockheed, a contractor for JSC. The run was for 700 seconds without stopping. There were 79 primary thruster firings during one maneuver.

An initial amount of propellant is used to get the maneuver rate up to 2°/sec. This amount is 18.38 lbs of propellant, which is also the amount it takes to stop the maneuver.

The amount of propellant it takes for attitude hold during a maneuver is 14.4 lbs. The total amount of propellant used during one maneuver is 51 lbs. This represents the amount of propellant it takes to start and stop the maneuver plus the amount it takes for attitude hold during the maneuver.

If two maneuvers are done back to back, the amount of propellant it takes to stop the first maneuver and start the second maneuver would be saved. This represents a total of 36.8 lbs of propellant saved each time the maneuvers are accomplished this way. If the targets that are required can be achieved by doing the maneuvers one right after the other, then a significant amount of propellant can be saved.

The total amount of propellant used during the entire mission was calculated using the case where none of the maneuvers were made back to back. This represents the worse case in terms of propellant usage.

SUMMARY OF LIDAR POINTING

- Established LIDAR pointing requirements imposed on the Orbiter
- Orbiter can provide the SCALE pointing and stability
- Propulsion needed for scan and pointing modes are within the Orbiter capability
- Propellant margins exist for mission sharing

SUMMARY OF LIDAR POINTING

The Orbiter will be used to point the LIDAR and perform the scanning maneuver in the yaw direction about the local vertical. A 2°/sec maneuver rate is imposed as a requirement to achieve an overlap in the ground track so a target on Earth is pointed at from different angles.

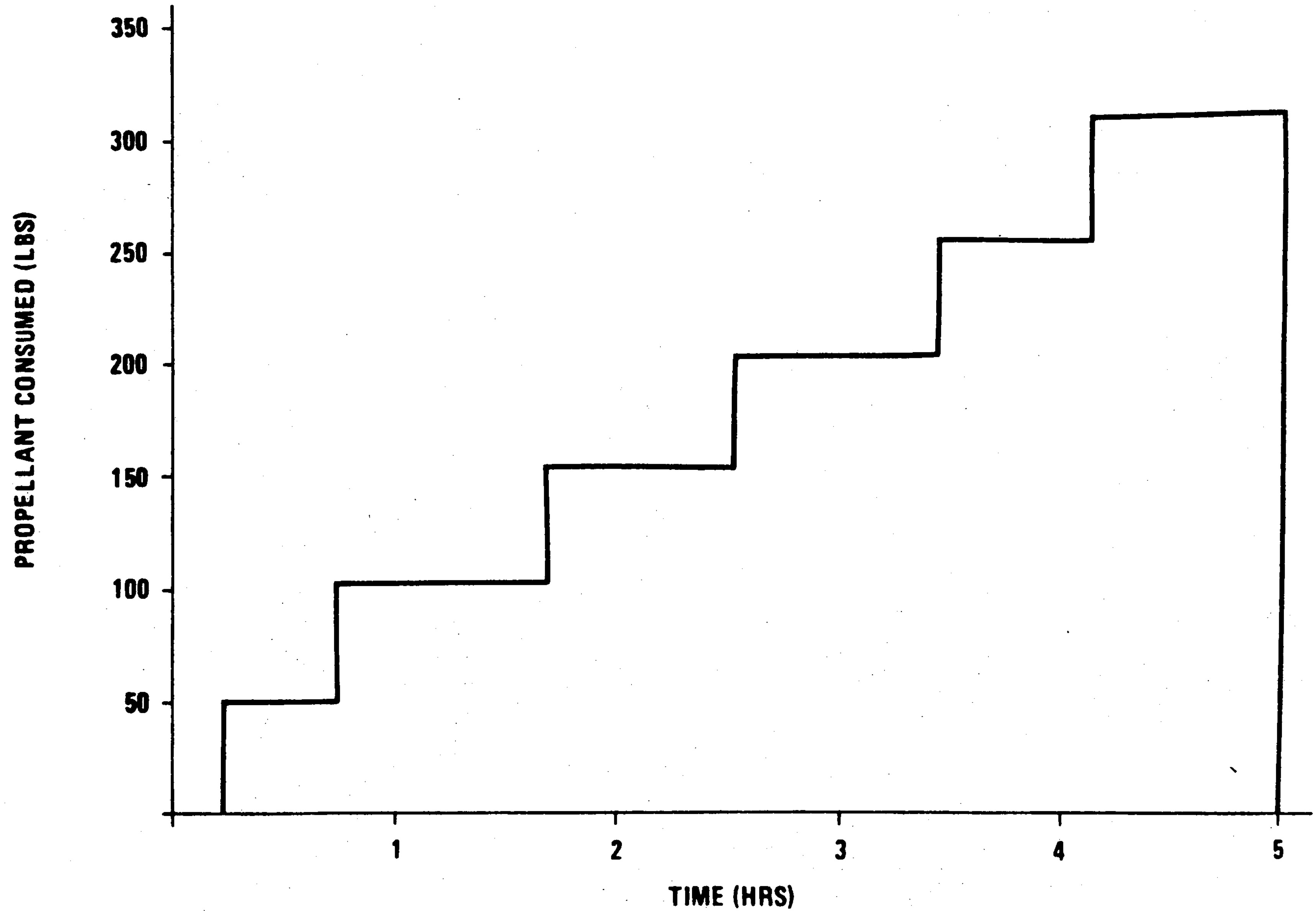
JSC did a simulation with the Orbiter maneuvering at 2°/sec. They found that the Orbiter could hold a $\pm 0.5^{\circ}$ deadband. This would produce a minimum error of $\pm 2^{\circ}$ and a maximum error of $\pm 2.5^{\circ}$ depending on the drift time. Also, from the simulation the propellant consumption was found to be 23.5 lbs from the forward tank and 27.5 lbs from the aft tank per maneuver.

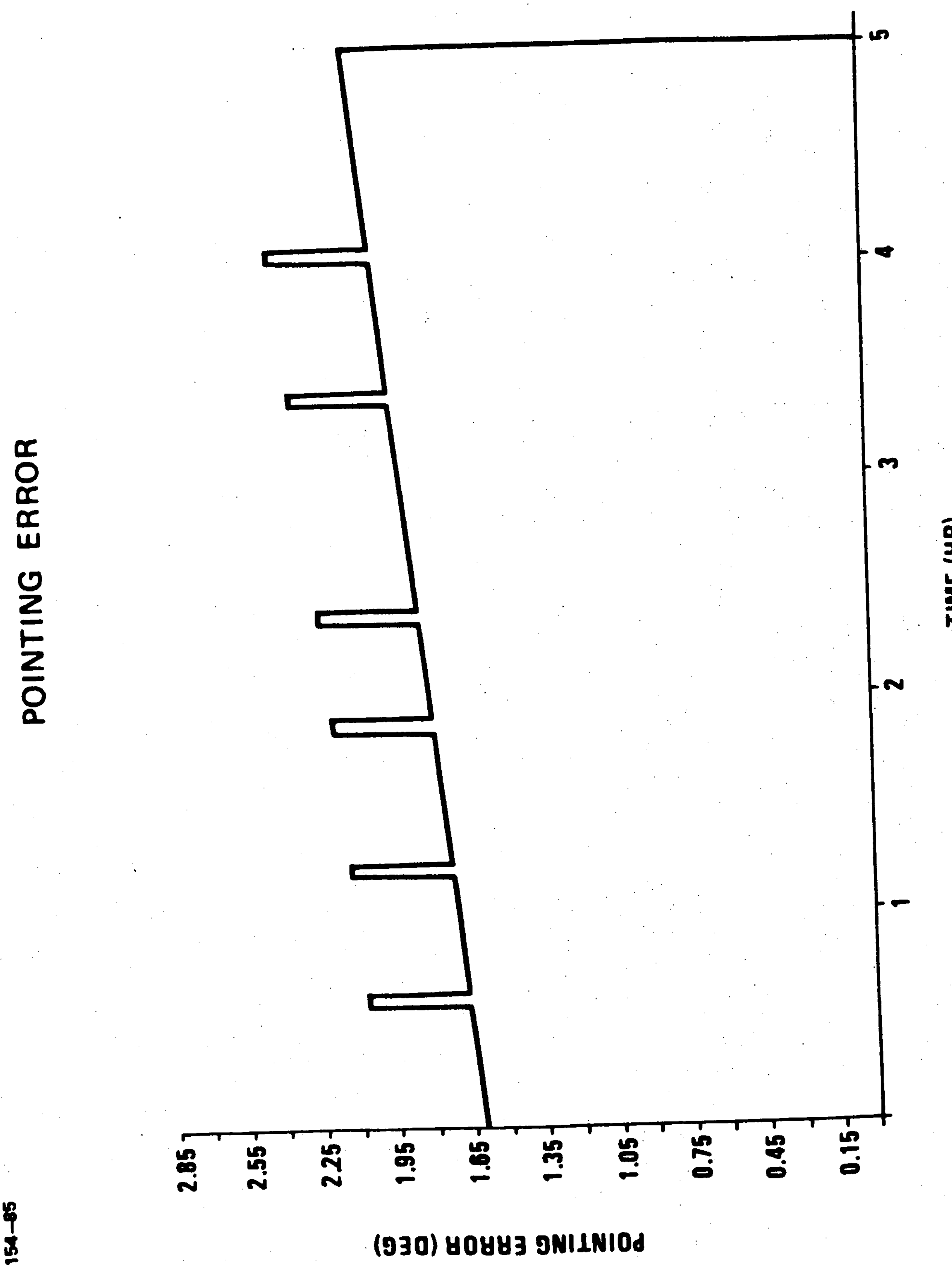
The experiment will be on for 5 hours a day, during which the Orbiter will be in an aircraft position with the LIDAR pointed toward the Earth at 45° off nadir. The Orbiter will be in this position unless conducting a yaw maneuver. It was determined that the yaw maneuver was needed twice per orbit, so the targets desired will be achieved.

The pointing accuracy of $\pm 2.5^{\circ}$ was determined to be sufficient for the experiment. The total propellant that will be used during the mission is 1117 lbs from the forward tank and 1305 lbs from the aft tank. This leaves 538 lbs from the forward tank and 95 lbs from the aft tank for mission sharing. The propellant from the forward tank will be the limiting factor because extra propellant can be bought from the OMS tank for use in the aft tank.

SCALE
4155—85

PROPELLANT CONSUMED PER DAY





SCALE
4154-85

SCALE

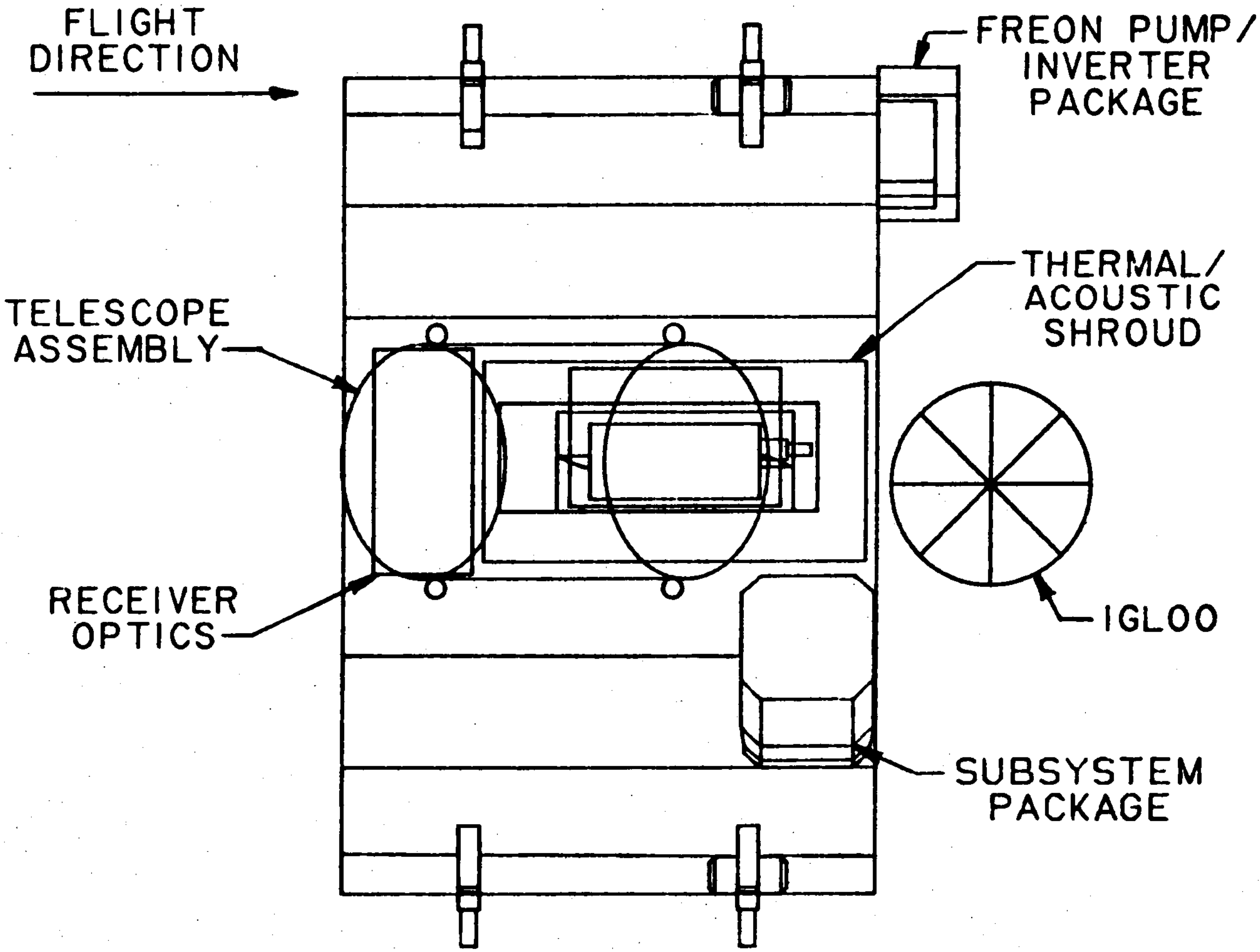
CONFIGURATION

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)
TOP VIEW

This view shows the SCALE mounted on a standard 3 meter pallet, including an igloo and standard subsystem packages. The 3 meter pallet was chosen because (1) it is standard, available, flight qualified hardware (2) it has adequate volume and support capabilities and (3) would represent the lowest cost approach to accommodate the experiment. The igloo would provide support services to SCALE in case the rest of the Orbiter payload does not include a Spacelab. The SCALE is offset from the pallet longitudional axis only enough to allow clearance for the subsystems package. This arrangement allows maximum access to the SCALE components on the pallet and also to the 24 attachment fittings on the pallet.

SCALE

SHUTTLE COHERENT ATMOSPHERIC
LIDAR EXPERIMENT (SCALE)
TOP VIEW



7-23-85

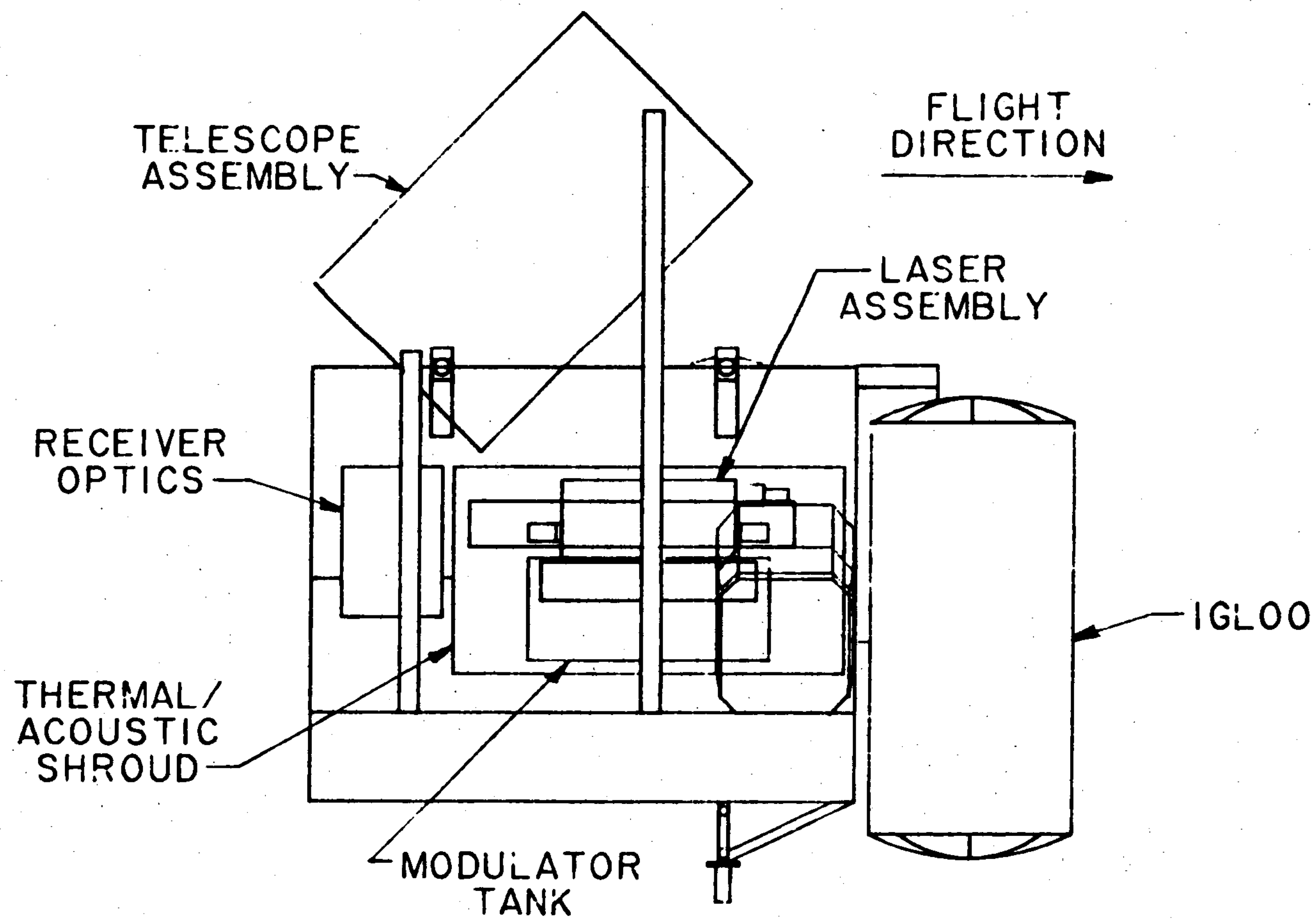
SCALE

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)
SIDE VIEW

This view shows the arrangement of the major components of SCALE mounted on the 3 meter pallet. The laser assembly and modulator tank are mounted within a thermal/acoustic shroud which, in turn, is securely fastened to several of the pallet hard points. The telescope assembly is a 1 meter diameter class by 2 meter length telescope as shown. These dimensions are preliminary and subject to change after an optics trade study has been run. The telescope is inclined 45^{o} from the vertical and is supported by a truss type structure from the pallet. The receiver optics is shown as a separate package located adjacent to the telescope and thermal/acoustic shroud. The pallet is secured to the Orbiter by 4 sill fittings, located at the top of the pallet, and 1 keel fitting located beneath the pallet.

SCALE

SHUTTLE COHERENT ATMOSPHERIC
LIDAR EXPERIMENT (SCALE)
SIDE VIEW



8-7-85

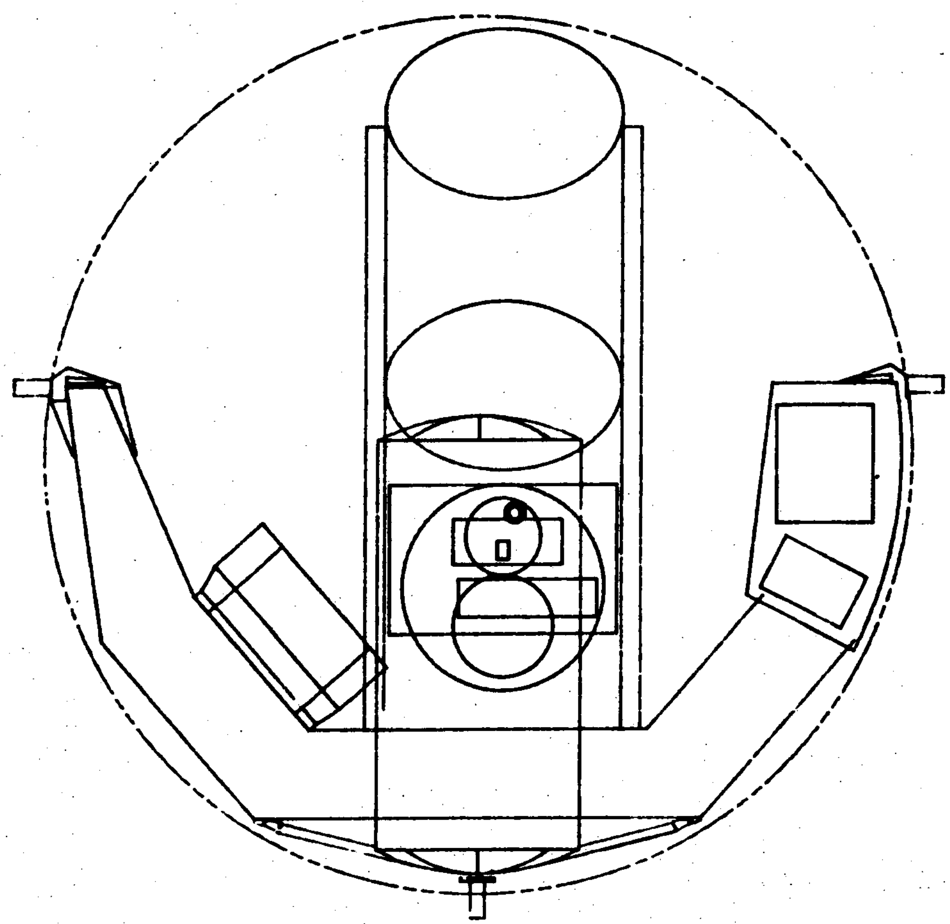
SCALE

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)
END VIEW

This view shows SCALE translated sideways to clear the pallet subsystems package. The pallet sill and keel fittings are shown along with the 15 foot diameter Orbiter cargo bay interior envelope (shown in Phantom line).

SCALE

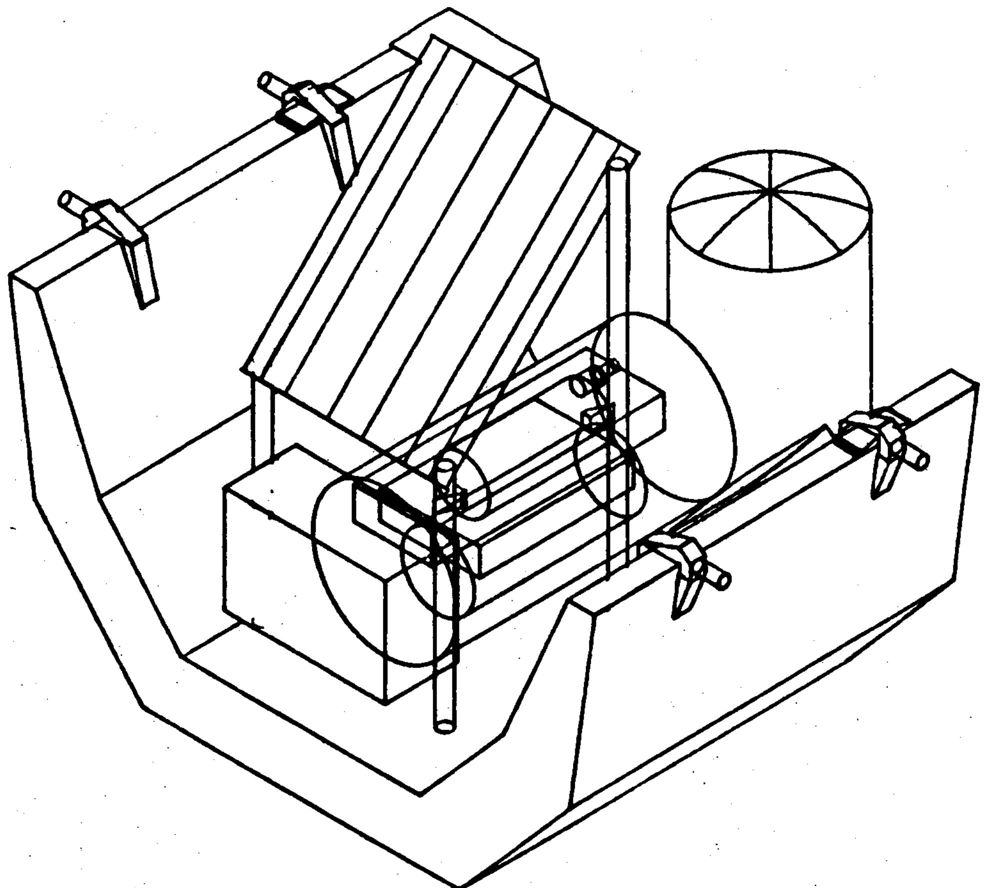
SHUTTLE COHERENT ATMOSPHERIC
LIDAR EXPERIMENT (SCALE)
END VIEW



8-7-85

SCALE

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)



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SCALE

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

COMPONENTS LIST

AUGUST 8, 1985

		SIZE
1.	PALLET WITH IGLOO	
2.	THERMAL/ACOUSTIC SHROUD	42" DIA X 81" LONG
3.	MODULATOR TANK (INSIDE T/A SHROUD)	22" DIA X 50" LONG
4.	LASER ASSEMBLY (INSIDE T/A SHROUD)	16" DIA X 53.8" LONG
5.	TELESCOPE ASSEMBLY	49.21 DIA X 74.74" LONG
6.	RECEIVER OPTICS	21" LONG X 47.25" W X 30.5" H

SCALE

WEIGHTS

SCALE

SCALE

WEIGHT SUMMARY (KG)

SUBSYSTEM	WEIGHT
LASER (MECHANICAL)	225
LASER (ELECTRICAL)	455
THERMAL	48
C^3	30
OPTICS ASSEMBLY	30
STRUCTURAL SUBSYSTEM	150
ACOUSTIC SHELL AND LEAD FOAM	300
TABLE AND SPACE FRAME INCL. REC. OPTICS	100
SUBTOTAL LASER EQUIPMENT	1338
TELESCOPE	605
MTG STR	67
CONTINGENCY 10%	206
TOTAL EXPERIMENT WEIGHT	2216
MDE	
EXP. HX	14
COLD PLATES + SPRT FOR (3) + PLUMB.	52
TOTAL PALLET PAYLAOD	2282

NOTE: SPACELAB PALLET NOMINAL LOAD CARRYING CAPABILITY FOR PAYLOAD AND MISSION DEPENDENT EQUIPMENT (MDE), WITH AN IGLOO, IS 2880 KG.

WEIGHT SUMMARY

These are preliminary weights shown for the SCALE study. The 605 kg and 67 kg listed for the telescope and mounting structure, respectively, are conservative weights up to a 1¼m. diameter telescope. Since most of the laser equipment is considered as developed hardware from the NOAA project, a 10% contingency (VS 15%) was used. Total weight of 2282 kg allows a 598 kg margin for Spacelab pallet nominal load carrying capability of 2880 kg for payload and mission-dependent equipment, when used with an igloo.

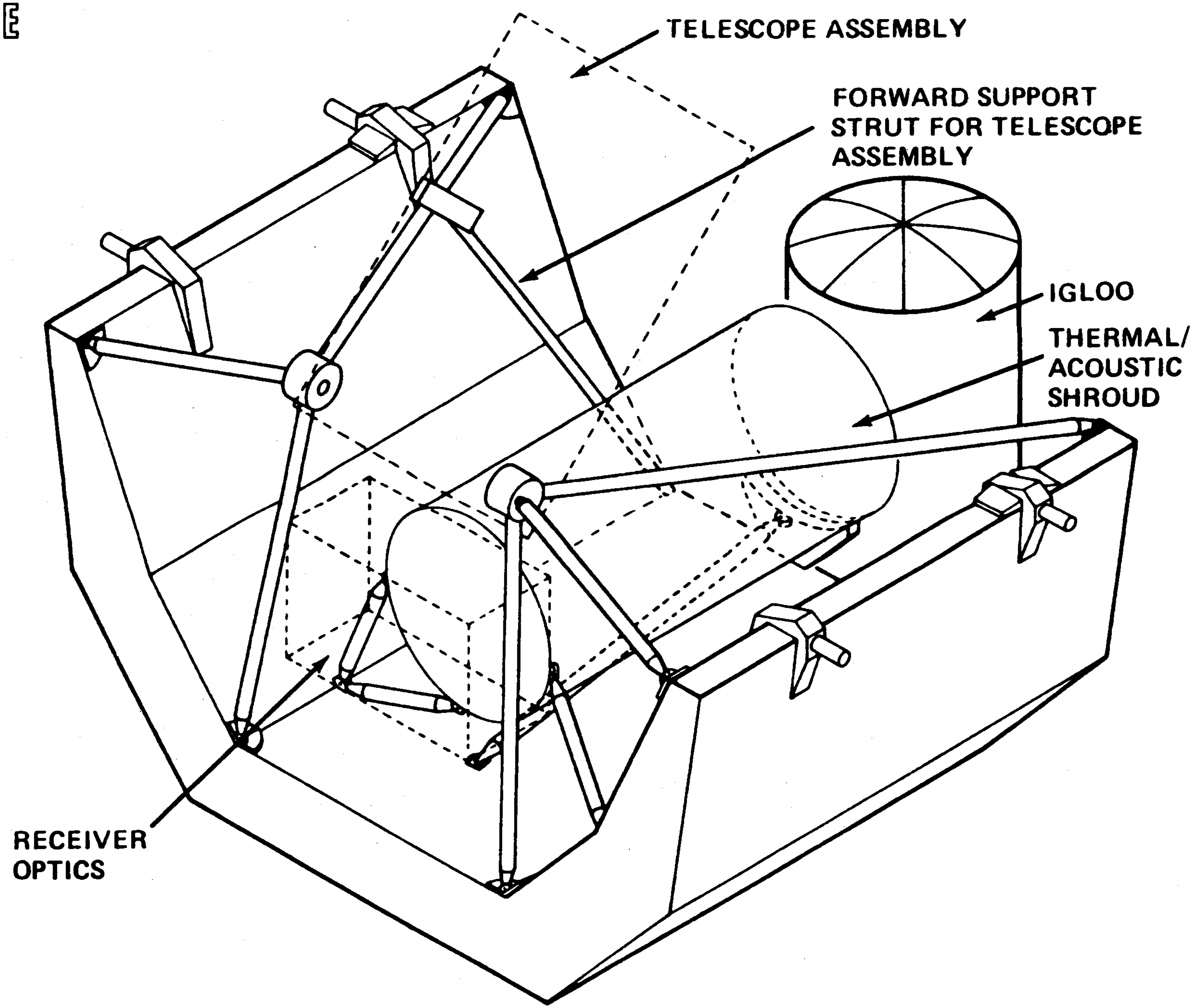
STRUCTURES

SHUTTLE COHERENT ATMOSPHERIC EXPERIMENT (SCALE)

This illustration shows how the telescope assembly and the thermal/acoustic shroud are supported on the pallet. The telescope assembly is supported by seven struts as shown. Two sets of three struts attach to the aft ring (not shown) of the telescope assembly to stabilize the telescope in the X, Y, and Z directions and in roll and yaw. A forward support strut stabilizes the telescope in pitch. The Y loads of the telescope assembly are reacted through one side of the pallet only. At this time it is assumed that the receiver optics assembly will be structurally attached to the telescope assembly.

The thermal/acoustic shroud provides thermal and acoustic protection for various subsystems such as the laser system and the modulator tank, and acts as a structural support system as well. The shroud is supported to the pallet by four struts and a forward-mounted saddle. The shroud is a stiffened cylinder with forward and aft rings (not shown) and with forward and aft hatches to permit access from either end.

SCALE

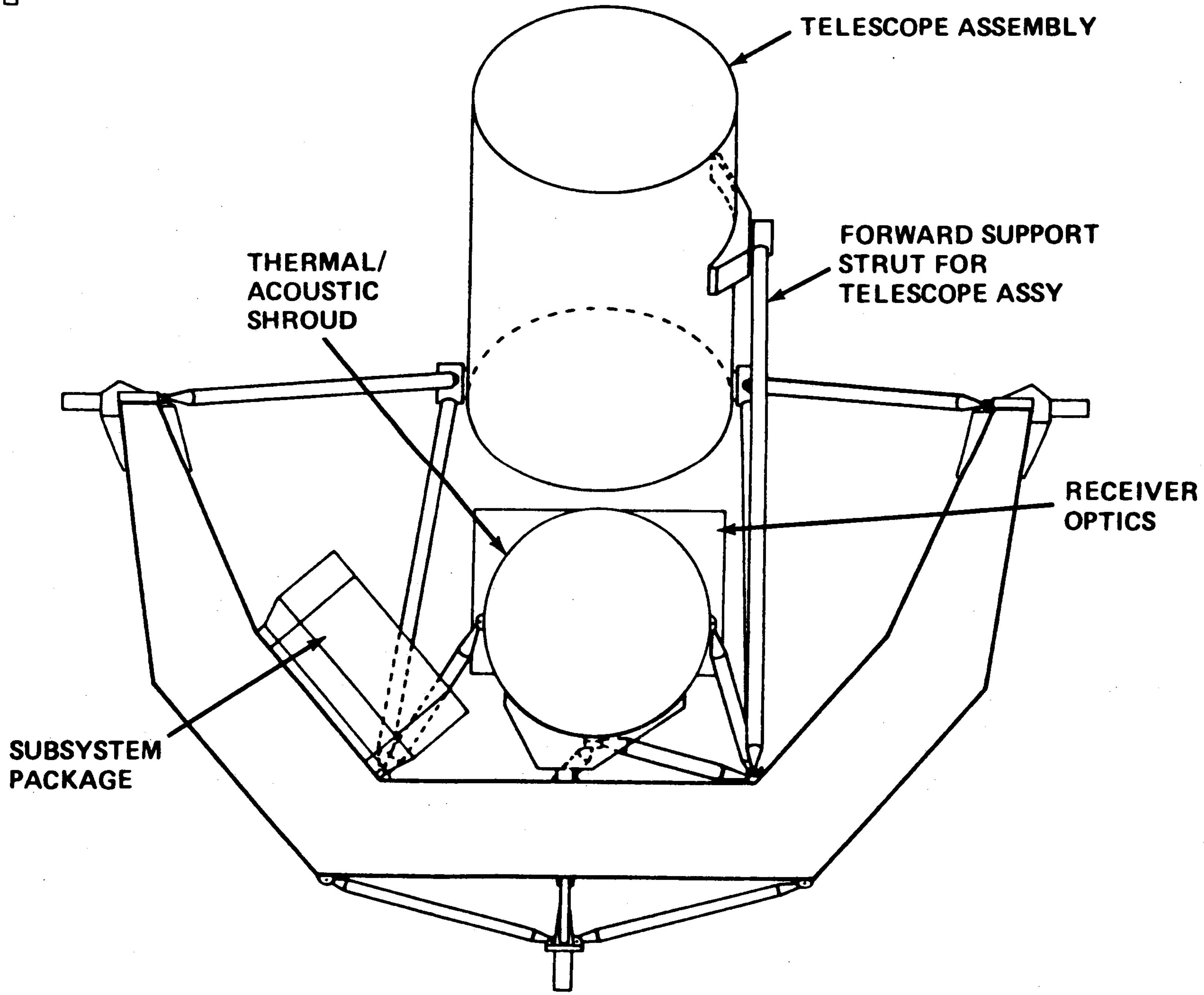


SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

This view is from the front of the pallet looking aft with the igloo removed for clarity. The primary systems are shown with callouts. All pallet structural hardpoints utilized are standard.

SCALE



SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

THERMAL

SCALE

SCALE
SPACELAB PALLET ACTIVE THERMAL CONTROL

SCALE/SPACELAB PALLET ACTIVE THERMAL CONTROL (ATCS) ORBITER THERMAL CONSTRAINTS

An overview of the Spacelab Pallet thermal control provisions is presented. The thermal management approach is to insulate the equipment on the pallet isolating it from the space environment. Heat can then either be added or removed to regulate the temperature. The primary task in providing temperature control is to remove heat from the equipment while it is operating. This is accomplished with the pumped coolant fluid loop. Additional Spacelab subsystem characteristics can be obtained from the Spacelab Accommodation Handbook (SLP/21043). The primary Orbiter thermal constraints are shown on the facing page.

ORBITER THERMAL CONSTRAINTS

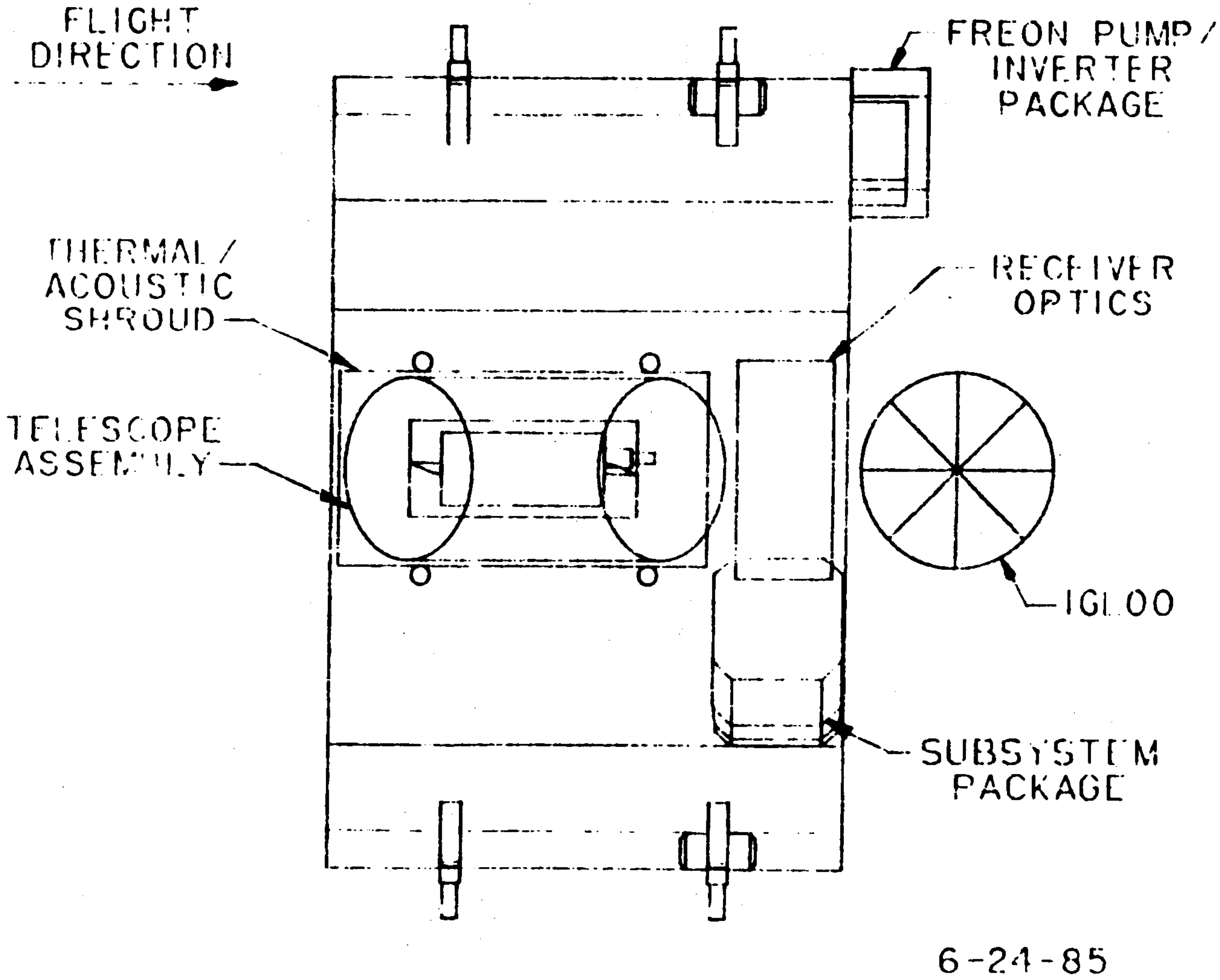
- OPERATING FLUID TEMPERATURES
  - 4°C FROM ORBITER
  - 40°C TO ORBITER
- MAXIMUM HEAT REJECTION
  - PAYLOAD BAY
    - 1.5KW DURING ASCENT/DESCENT
    - 8.5KW ON-ORBIT
  - AFT FLIGHT DECK
    - 0.35 KW DURING ASCENT/DESCENT
    - 0.75 KW ON-ORBIT

SCALE/SPACELAB PALLET ATCS
LAYOUT ARRANGEMENT

Shown on the layout is the Freon Pump/Inverter Package for the Spacelab Pallet pumped coolant loop. Cold Plates for the Communications, Data Management, and power control equipment are located inside the Igloo. The subsystem package consists of additional subsystem equipment (experiment power distribution box, remote acquisition units and interconnect station) mounted on a cold plate. An Experiment Heat Exchanger will be located on the pallet near the Lazer Assembly. The Orbiter Payload Heat Exchanger is underneath the payload bay liner in the forward portion of the payload bay.

SCALE

SHUTTLE COHERENT ATMOSPHERIC
LIDAR EXPERIMENT (SCALE)
TOP VIEW



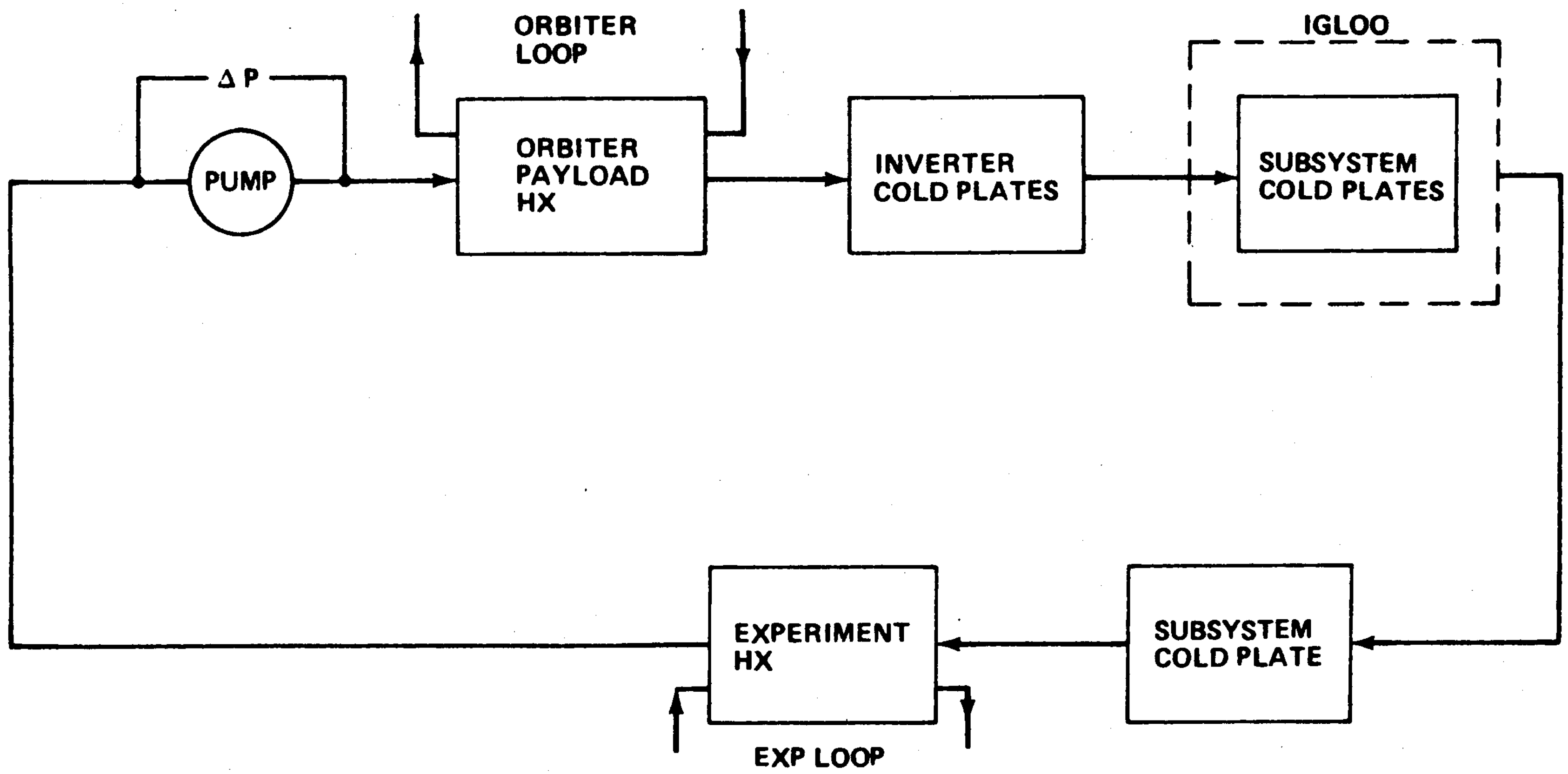
SCALE/SPACELAB PALLET ATCS
CONCEPTUAL LAYOUT WITH SERIES FLOW

A conceptual layout of the Spacelab Pallet pumped coolant fluid loop with series flow is shown here. The Igloo mounted equipment requires a coolant temperature near the Payload Heat Exchanger fluid exit temperature. Therefore, all experiment cold plates/HX are located downstream of the Igloo. The Experiment Heat Exchanger permits integration of the experiment onto the pallet without breaking into the Spacelab Pallet pumped fluid loop.

SCALE

4234–85

SCALE ATCS CONCEPTUAL LAYOUT



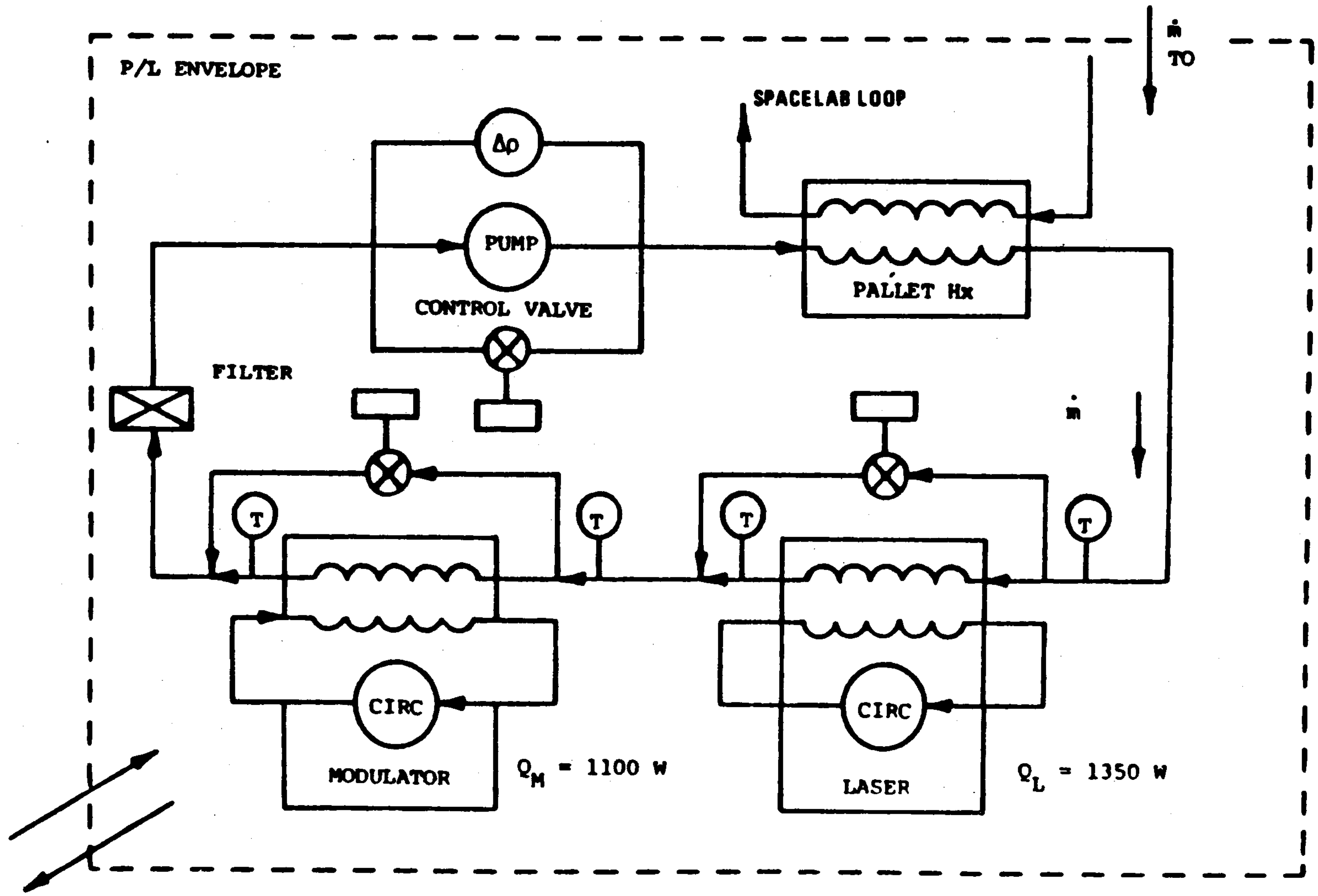
SCALE/SPACELAB PALLET ATCS
EXPERIMENT COOLANT LOOP

Shown here is the experiment coolant loop that interfaces with the Spacelab Pallet coolant loop Experiment Heat Exchanger. This is part of the experiment provided equipment. The operating temperatures and coolant flowrate requirements will need to be established to assure adequate thermal control of the experiments.

4198–85

SCALE

THERMAL SYSTEM SCHEMATIC



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Spectra Technology
(formerly MSNW)

SCALE/SPACELAB PALLET ATCS
COMPONENT PRESSURE DROPS

Shown here are pressure drops in components that can be used to make up the Spacelab Pallet pumped loop. The total loop allowable system pressure drop is approximately 58 psi of which approximately 28 psi is required by the Spacelab subsystem hardware.

SCALE

COMPONENT PRESSURE DROPS

	FLOW RATE (LBM/HR) 1000	2000
HARDLINES	0.57 PSI/100 FT	1.94 PSI/100 FT
FLEXLINES	1.42 PSI/100 FT	5.76 PSI/100 FT
COLD PLATES		
DFI	25.42 PSID	93.18 PSID
HAMILTON STANDARD	1.41 PSID	4.27 PSID
FSA	0.16 PSID	0.60 PSID
QUICK DISCONNECT	0.16 PSID	0.54 PSID

SCALE/SPACELAB PALLET ATCS
EXPERIMENT HEAT EXCHANGER PRESSURE DROP

Shown here are Experiment Heat Exchanger pressure drops as a function of flow rate. Water side pressure drop with Freon coolant is yet to be demonstrated. It is expected to be only slightly higher than the Freon side pressure drop with Freon coolant.

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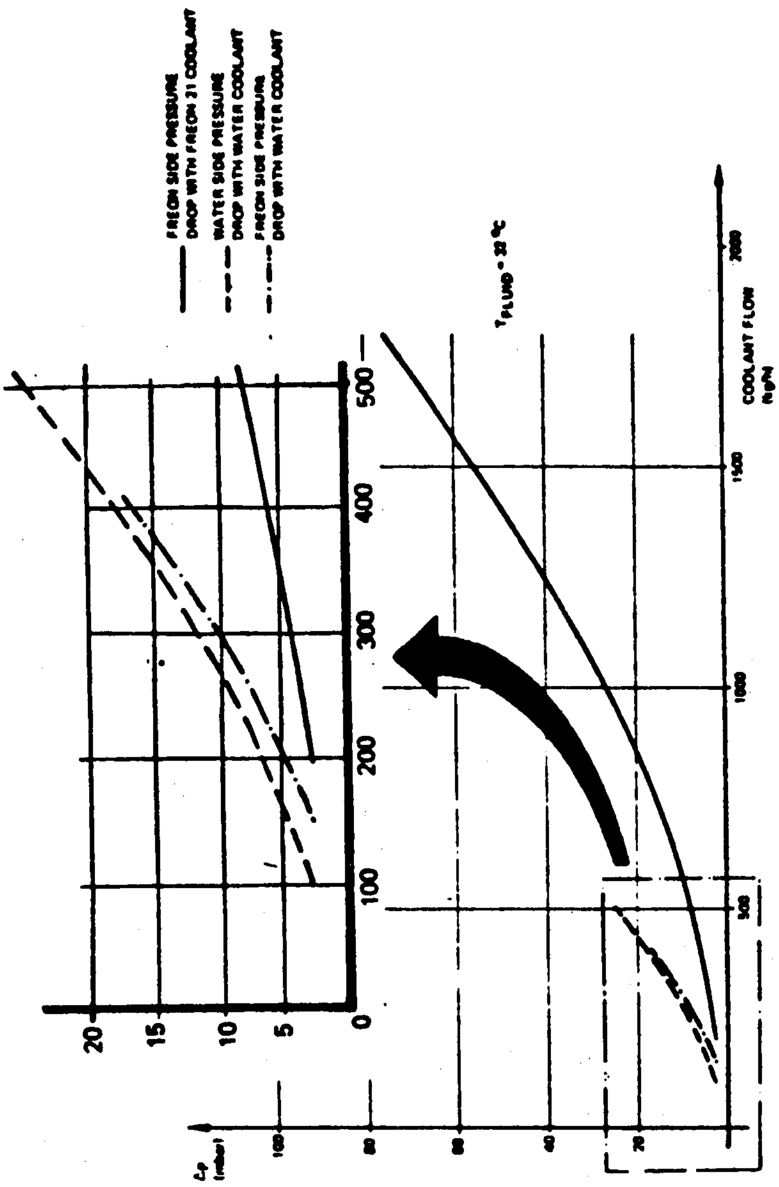
OF POOR QUALITY



C5-94

Figure 5.4-14: EHX Pressure Drop

SCALE/SPACELAB PALLET ATCS
PRELIMINARY HEAT REJECTION AVAILABILITY

The maximum allowable heat rejection for payloads in the Orbiter bay is listed here under non-shared configuration. If SCALE were the only payload, 29,010 BTU/HR total heat rejection would be available. In the presently proposed arrangement, SCALE would share the Orbiter bay with another payload and 17,065 BTU/HR would be available. Although the available heat rejection is 29,000 BTU/HR (8.5 KW), the electrical power is restricted by the Orbiter to 7 KW total for all payload equipment (including Spacelab subsystems).

4197-85

SCALE

SCALE/SPACELAB PALLET ATCS PRELIMINARY HEAT REJECTION AVAILABILITY

	SHARED CONFIGURATION	NON-SHARED CONFIGURATION
TOTAL AVAILABLE HEAT REJECTION	17,065 BTU/HR	29,010 BTU/HR
REQUIRED FOR SUBSYSTEM*	9,460 BTU/HR	9,460 BTU/HR
AVAILABLE FOR EXPERIMENTS	7,605 BTU/HR	19,550 BTU/HR

*SUBSYSTEM REQUIREMENTS DO NOT INCLUDE PLUMBING LINE HEAT GAIN (5 BTU/HR PER FOOT MAX. WITH MLI)

SCALE

ELECTRICAL POWER

SCALE ELECTRICAL POWER BUDGET

A breakdown of the total continuous power requirements for SCALE have been provided. This breakdown consists of experiment (Science Instruments) power and subsystem power required during operation. The anticipated total power is shown as 4,994 watts. This power level is within the payload power accommodations provided by the Orbiter in the "mixed cargo" mode (5 kW max. continuous).

SCALE ELECTRICAL POWER BUDGET

SCIENCE INSTRUMENTS	POWER REQUIRED (WATTS)
LASER (MECHANICAL)	75
LASER (ELECTRICAL) AT 25 Hz REPETITION RATE	1,300
THERMAL (ONE PUMP)	315
C^3	100
OPTICAL/STRUCTURAL	250
	2,040
SPACELAB (IGLOO AND PALLET)	
SUBSYSTEMS	
C&DM (W/HDR OPTION)	1,955
THERMAL	375
DISTRIBUTION AND CABLE LOSS (5%)	111
CONTINGENCY (15%)	333
TOTAL	4,814 WATTS

SCALE AND ORBITER POWER/ENERGY

The power and energy available to the Shuttle Payload Bay is shown, assuming the standard three fuel cell tank sets, and also, for an additional fuel cell tank set (4th).

The SCALE (anticipated) power and energy requirements for a seven-day, 4-5 hr/day mission are provided. Comparing the power available vs. power required indicates that additional power (approximately 2 kW) will be available for other payloads. A similar comparison of the energy requirements show that the fourth fuel cell tank set will be necessary. This extra tank set will provide sufficient energy for SCALE and additional energy capacity of approximately 540 kWh to meet energy requirements for other Shuttle payloads.

The conclusions resulting from this data are:

1. The amount of electrical power supplied by the Orbiter is sufficient for the SCALE Experiment.

2. In order to supply the electrical energy required for this experiment, a fourth fuel cell tank set must be added to the standard Shuttle complement.

SCALE

SCALE AND ORBITER POWER/ENERGY

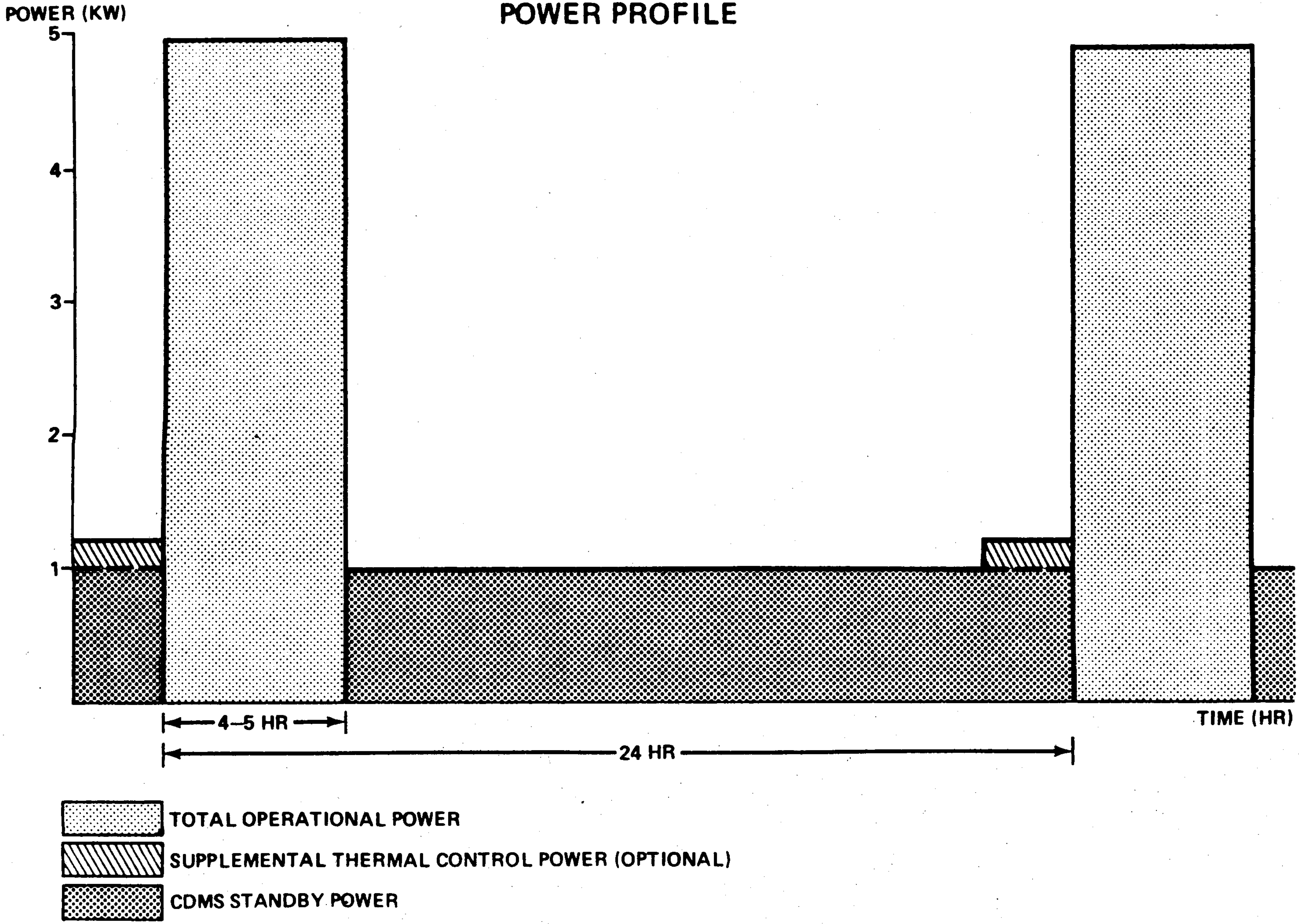
	POWER	ENERGY
ORBITAL CAPACITY	7 KW	50 KWH
EXTRA FUEL CELL TANK SET	7 KW	840 KWH
SCALE (7-DAY, 4-5 HR. OPERATION)	5 KW	280 TO 315 KWH

SCALE POWER PROFILE

The Power Profile as shown in the following chart illustrates the proposed power required during experiment operation and standby power required by the Spacelab CDMS subsystem equipment. This profile represents a typical 24-hour timeline for the SCALE experiment with the thermal control power being optional if additional heating is required.

SCALE
4093–85

SCALE
POWER PROFILE



SCALE

SCALE

COMMUNICATIONS AND DATA MANAGEMENT SYSTEM

SCALE

SCALE

CDMS REQUIREMENTS

- HOUSEKEEPING
  - 120 KB/S DOWNLINK
  - REQUIRES SHUTTLE STATUS (POSITION, ATTITUDE, ETC.)
  - TEMPERATURE, PRESSURE, VOLTAGE, POWER, ETC. FROM EXPERIMENT
- SCIENCE DATA
  - RAW DATA
    - UP TO 3.5 MB/S DOWNLINK
  - PROCESSED DATA
    - 18 KB/S DOWNLINK
    - PROCESSED BY EXPERIMENT
    - DOPPLER MOMENTS AND CALCULATIONS
- VIDEO DATA
  - BORESIGHTED TV CAMERA
  - 4.5 MHZ CHANNEL
  - MAY RECORD DURING PEAK DATA DOWNLINK

SCALE CDMS REQUIREMENTS

The SCALE CDMS requirements have been divided into three basic categories: Housekeeping, Science Data and Video.

The Housekeeping data is defined as that data which is required by the experiment from the Shuttle Orbiter, such as position, velocity, attitude, etc. There will also be housekeeping data which gives the status of the experiment, such as temperature, voltage, power, etc.

The Science data from the experiment has been classified as Raw data and Processed data. All raw data will be sent to the data system for downlinking; in addition, part of the raw data will be processed by the experiment. Doppler moments will be extracted and certain calculations will be done. This processed data will also be fed back to the Orbiter for downlinking.

Video data will consist of one standard video channel, fed from a boresight TV camera mounted on the experiment. Some of the video data may be recorded on the Orbiter video recorder during peak data downlink.

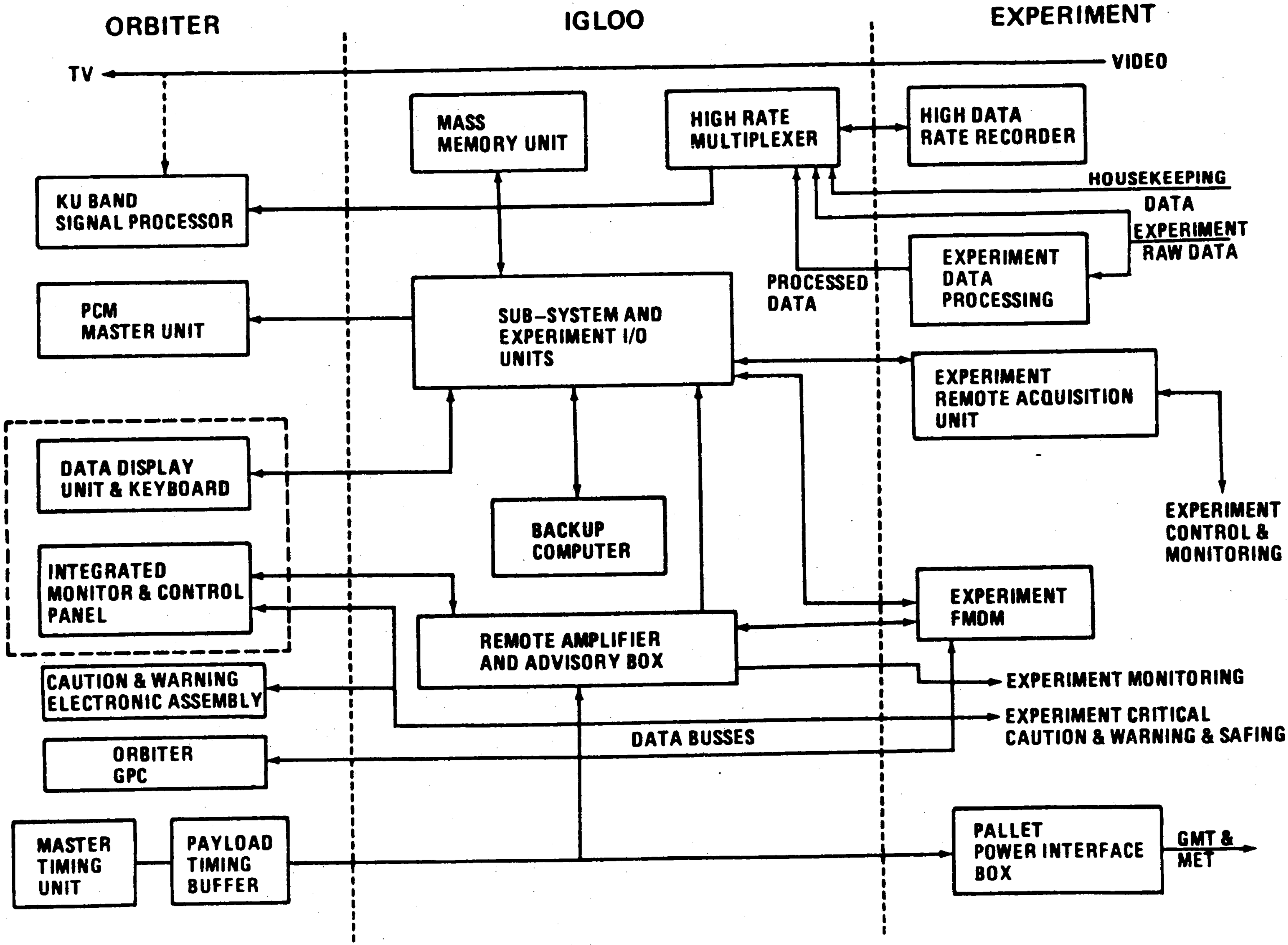
SCALE
CDMS REQUIREMENTS (CONTINUED)

- TOTAL DATA REQUIREMENT
  - 3.6 MB/S PLUS TV CHANNEL
  - DOWNLINK ALL DATA DURING NORMAL OPERATION
  - RECORD DATA WHILE IN MANEUVER
  - DOWNLINK RECORDED DATA WHILE OVER TARGETS OF NO INTEREST

SCALE CDMS REQUIREMENTS (CONTINUED)

The total amount of data to be handled is approximately 3.6 megabits/second, not including the TV signal, which is dependent on the required resolution and frame rate. All the data can be downlinked via the Ku-band while the Orbiter is in level flight, but all data will be recorded on the High Data Rate Recorder while in the 6-minute flat spin maneuver. This recorded data can then be downlinked later while the Orbiter is over a ground track of little or no interest.

3818–85
SCALE



SCALE CDMS CONFIGURATION

SCALE CDMS CONFIGURATION

The SCALE CDMS configuration has been divided into three basic areas; Orbiter, Igloo and Experiment. The data is generated in the experiment and fed back to the High Rate Multiplexer, both in raw and processed form. From there, it goes to the Ku-band signal processor and is downlinked to the ground through TDRSS. It also may be sent to the High Data Rate Recorder for storage; tolbe downlinked at a later time. The video signal from the experiment is sent back to the Orbiter video control unit where it is available for downlinking, recording or on-board displays. Selected data from the experiment may be monitored on the Data Display Unit in the Orbiter and control of the experiment is provided from the Integrated Monitor and Control Panel. Shuttle position and status data is provided to the experiment from the Orbiter's general purpose computer and timing data is provided from the Master Timing Unit. Monitoring of the experiment for critical safing and caution and warning is also provided.

SCALE

SCALE
HIGH DATA RATE RECORDER CHARACTERISTICS

RECORD TECHNIQUE	LONGITUDINAL, 28 TRACKS
DATA TRACKS	24
DATA STORAGE	3.8×10^{10} BITS
BIT DENSITY/TRACK	20 KB/INCH
DATA RATE RECORD	1, 2, 4, 8, 16, 32 MB/S OR 1 THRU 32 MB/S VIA DIRECT ACCESS
DATA RATE REPRODUCE	2, 4, 8, 12, 16, 24, 32 MB/S
TOTAL RECORD TIME	FROM 20 MIN. AT 32 MB/S TO 640 MIN AT 1 MB/S
DATA TYPE	SERIAL IN, SERIAL OUT, NRZ-L + CLOCK,, GROUP CODING ON TAPE
BIT ERROR RATE	LESS THAN 1 IN 10^6 BITS WITH SCREENED TAPE
REPRODUCE DIRECTION	REVERSE TO RECORD DIRECTION
START/STOP TIME	5s
TAPE HANDLING	TAPE CHANGE CAPABILITY WITH AUTOMATIC THREADING
TAPE HANDLING TIME	0.5 MIN. FOR ATTACHMENTS PLUS TIME FOR WIND/REWIND
WIND/REWIND TIME	7.5 MIN. EACH MAX.
TAPE WIDTH/REEL DIAMETER	1"/14"
TAPE REEL WITH TAPE	3.8 KG

SCALE HIGH DATA RATE RECORDER CHARACTERISTICS

The High Data Rate Recorder will be used to record data during periods when direct transmission through TDRSS is not feasible. Characteristics of particular interest are the record and reproduce data rates, which provide up to 32 MB/S and are more than sufficient for this experiment. Also the total record time, which will provide over 500 minutes of data storage at the 3.6 MB/S rate, will be sufficient to record the entire 5 hours per day of anticipated operation if necessary.

KU BAND DOWNLINK MODES

PHASE MODULATION - MODE 1

- O Channel 1 - 192 KBPS Bi-Phase-L PCM and voice NSP
- O Channel 2 - Select one of four inputs
  - Payload Interrogator (PI) (Narrow band bent pipe from detached payload)
  - Payload digital output, 16 KBPS - 2 MBPS, NRZ-L, M, or S 16 KBPS 0 1.024 MBPS Biphase L, M, or S
  - Operational recorder dump
  - Payload recorder dump
- O Channel 3 - Payload digital output, 2-50 MBPS with clock, NRZ-L, M, or S

SCALE

KU-BAND DOWNLINK MODES

The anticipated mode of data transfer is by Ku-band using Phase Modulation in Mode I. This mode offers three independent channels of operation with channel 3 being the selected channel since it offers up to 50 MB/S rates, which are more than sufficient for this experiment.

SCALE

ORBITER VIDEO PROVISIONS FOR PAYLOADS

- CCTV SYSTEM
  - STANDARD MONOCHROME DISPLAYS AFD
  - COLOR CAN BE PROVIDED FOR RECORDED OR DOWNLINKED VIDEO
  - ELEVEN VIDEO INPUTS TO VCU
    FIVE INDEPENDENTLY SELECTABLE OUTPUTS AVAILABLE
- COMPONENTS OF CCTV SYSTEM
  - "STANDARD" CAMERAS (CHOICE OF LENS ASSEMBLY; B&W OR COLOR
  - MULTIPLE INPUT LOCATIONS AT BULKHEAD, KEEL IN PAYLOAD BAY
  - VIDEO CONTROL UNIT

    + CAN INTERLEAVE AUDIO AND MULTIPLEX CHANNELS FOR SPLIT SCREEN
  - VIDEO TAPE RECORDER - (MONOCHROME OR NTSC COLOR) 30 MINUTES/CARTRIDGE (72 MIN. ON LATER MISSION)
  - MONITORS: TWO B&W 8 IN. DIAGONAL DISPLAYS
- VIDEO OUTPUTS ASSIGNABLE TO PAYLOADS FOR RF DOWNLINKING, RECORDING OR ONBOARD DISPLAYS (OR RECORDING ON PAYLOAD PROVIDED RECORDER)

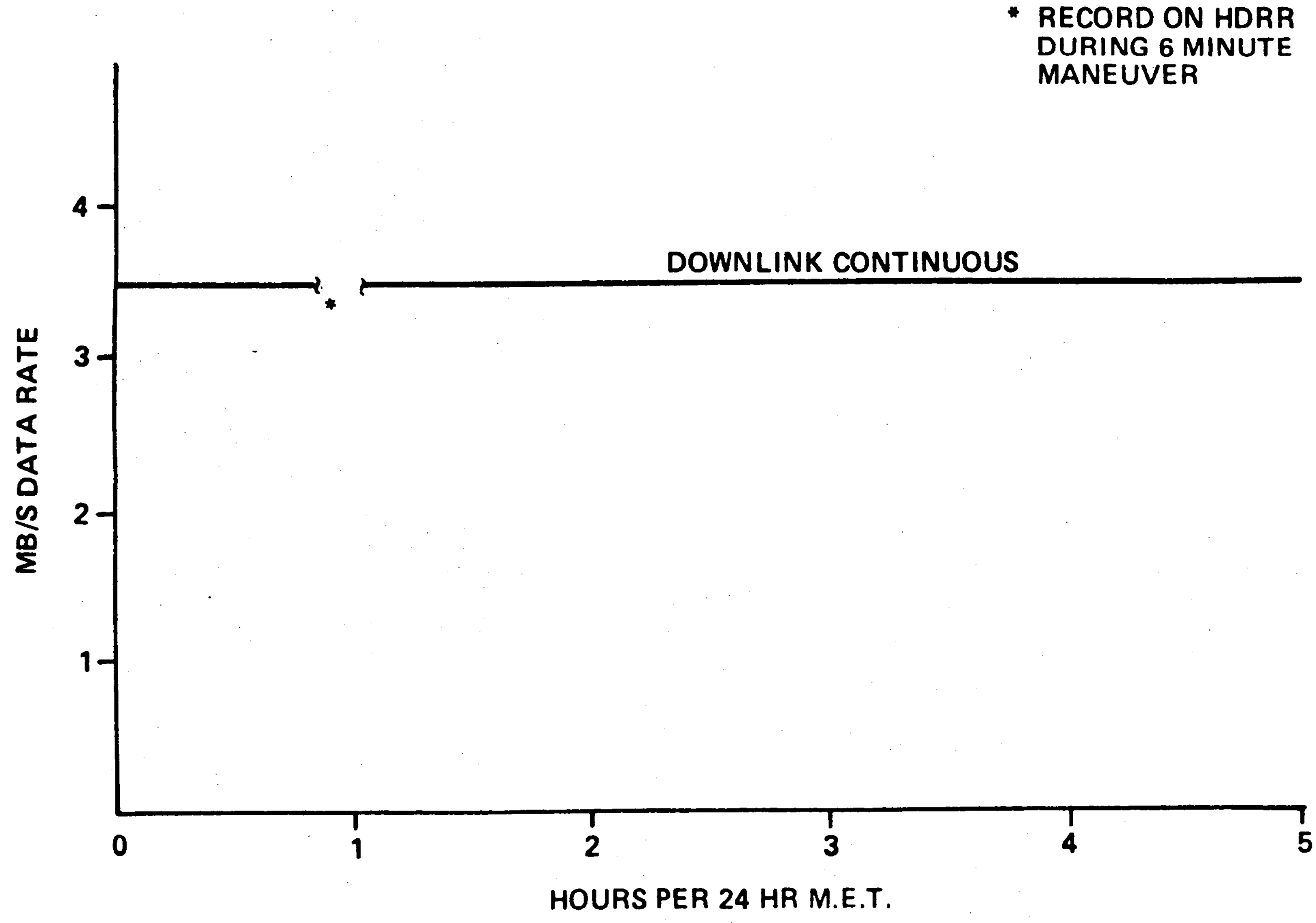
SCALE

ORBITER VIDEO PROVISIONS FOR PAYLOADS

The Orbiter closed-circuit TV system features standard monochrome displays on the aft flight deck, with color provided for recording or direct downlink. There are multiple inputs available to the Video Control Unit with a wide range of components which allow for downlinking, recording or on-board displays.

SCALE
4056—85

SCALE DATA COLLECTION TIMELINE



SCALE

SCALE DATA COLLECTION TIMELINE

The data collection timeline is shown for the 5-hour period of operation proposed for each 24 hours of mission elapsed time. Data will be collected and downlinked continuously except for the 6-minute spin maneuver, which will be recorded on the High Data Rate Recorder for later transmission.

CLOSED CIRCUIT TELEVISION

The CCTV system consists of the following major components:

(1) Video control unit - An interleave capability exists with audio channels A and B; multiplex capability is available for split screen. Remote command control of the camera lens and the pan/tilt functions, by both the crewman and the ground, is available. Eleven video inputs and five outputs are available for independent selection.

(2) Television cameras - A choice of lens assembly provides selection of either color or black and white. The Cargo Bay camera pan and tilt capability is ±170° at the rate of 1.2°/sec or 12°/sec. Zoom capability is either 30° to 80°, horizontal field of view, or 6.5° to 39°.

(3) Video Tape Recorder - Record capability is 30 min (increased to 72 min on later missions); monochrome or National Television Standards Committee (NTSC) color is available.

(4) Television monitors - Two black-and-white 8-in.-diagonal displays are provided.

SCALE

CLOSED CIRCUIT TELEVISION

The Orbiter CCTV system consists of 4 major components: A video control unit to select the video functions, a choice of color or black-and-white cameras, a 30-minute video tape recorder and 2 eight-inch B&W television montiors.

VIDEO TAPE RECORDER

Specifications

General:	
Video recording system	Rotary, 2 heads, helical scan system, frequency modulation (FM) recording
Video signal system	Electrical Industries Association (EIA) black-and-white or NTSC color
Power source	28 ± 4 Vdc unregulated
Power consumption	50 W (maximum)
Weight	50 lb
Operating temperature	-10° to +55° C
Operating humidity	0 to 80 percent relative humidity
Video signals:	
Input	1 Vp-p, negative sync, 75 ohms balanced
Output	1 Vp-p, negative sync, 75 ohms balanced, tip of sync direct current restored to 0 Vdc
Signal-to-noise ratio	>43 dB
Bandwidth	-8 dB, relative to 1 MHz, at 4.2 MHz
Audio signals:	
Input	-9 to +13 dBm, 0 dBm nominal, 600 ohms balanced
Output	+27 dBm maximum, 0 dBm nominal, 600 ohms balanced
Frequency response	200 Hz to 10 kHz, ±3 dB
Signal-to-noise ratio	>40 dB
Tape transport:	
Tape speed	95.3 mm/sec (3-3/4 in./sec)
Time base stability	10 μs relative to a field period
Recording time	30 min continuous time with KCS-30S video cassette 'S' tape

VIDEO TAPE RECORDER

The Orbiter Video Tape Recorder is a standard type of recorder utilizing an EIA black and white or NTSC color signal. It uses a 28 VDC power source with a low (50 watt) power drain. This recorder can be used to record up to 30 minutes of continuous video signal from an experiment, with cassette change provisions.

STUDY RESULTS

- Take an existing design and see if it can be space qualified.

  SRI says YES
  Use STI/NOAA "WINDVAN" CO_2 lidar system

- Can the experiment be accommodated on a Shuttle flight?

  PDO says YES

SUMMARY

SCALE

RESULTS

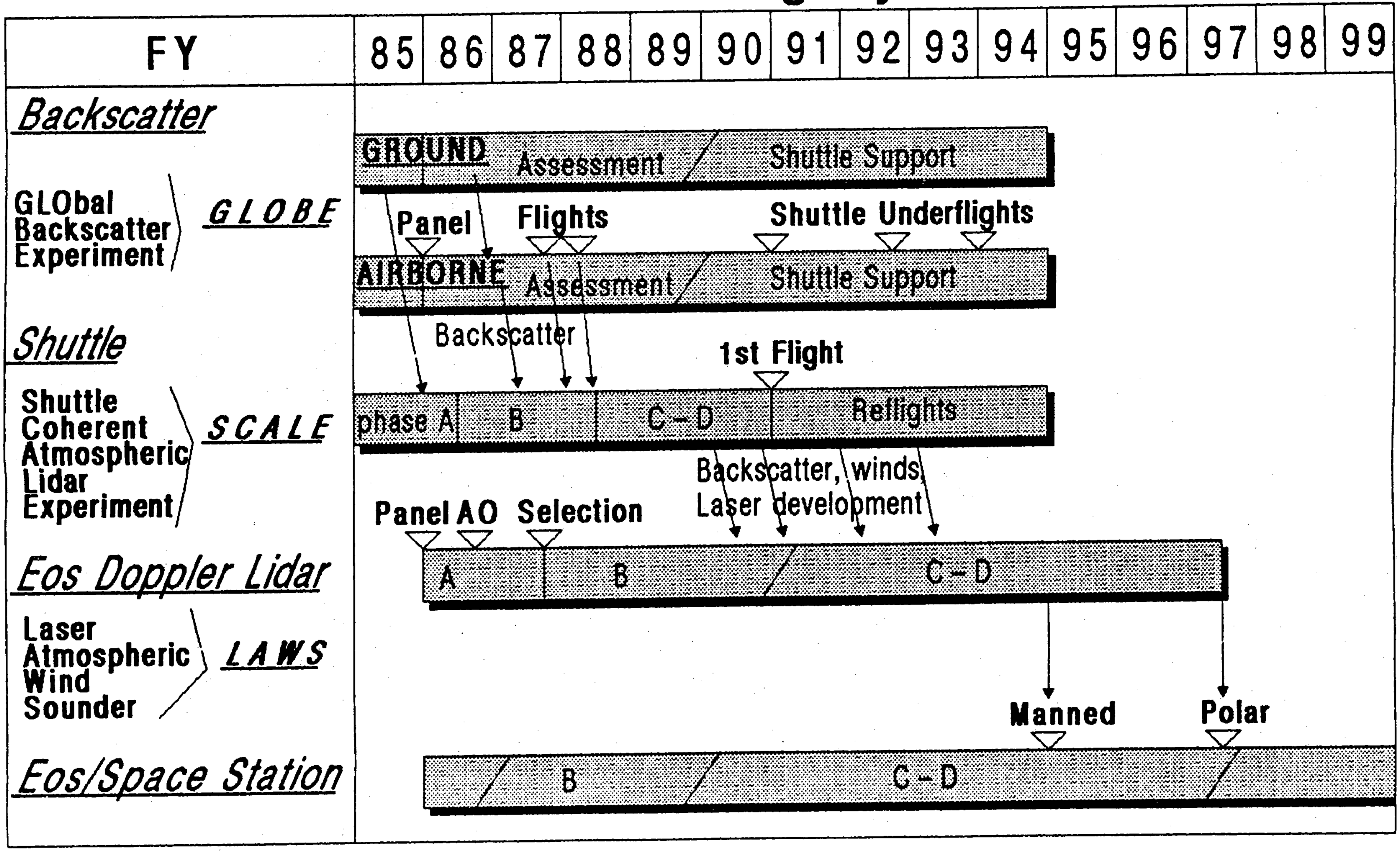
- A SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT HAS BEEN DESIGNED BASED ON AN EXISTING OPERATIONAL PULSED CO_2 LASER
- SPACE QUALIFICATION STUDIES HAVE SHOWN THAT THERE ARE NO SIGNIFICANT PROBLEMS INVOLVED IN QUALIFYING THE LASER FOR SHUTTLE FLIGHT
- ACCOMMODATION STUDIES HAVE SHOWN THAT THERE ARE NO SIGNIFICANT PROBLEMS INVOLVED IN ACCOMMODATING THE EXPERIMENT
- SYSTEM SENSITIVITY STUDIES HAVE SHOWN THAT VALUABLE SCIENTIFIC INFORMATION CAN BE OBTAINED RELATIVE TO THE GLOBAL DISTRIBUTION OF ATMOSPHERIC BACK-SCATTER AT 9.11 μM.
- SIGNIFICANT SCIENTIFIC INFORMATION CAN BE OBTAINED FROM SPACE-BASED WIND MEASUREMENTS

CONCLUSIONS

- SCALE PROVIDES THE FIRST OPPORTUNITY TO COLLECT SCIENTIFICALLY IMPORTANT WIND DATA FROM SPACE
- SCALE PROVIDES THE FIRST OPPORTUNITY TO COLLECT A GLOBAL DATA SET ON AEROSOL BACKSCATTER
- SCALE IS A NECESSARY STEP TO AN EOS SYTEM
- SCALE PROVIDES THE BREAK-THROUGH REQUIRED TO DEMONSTRATE SPACE-BORNE OPERATION AT A REASONABLE COST
- SUFFICIENT PALLETS EXISTS TO ALLOW THE ENTIRE EXPERIMENT TO BE STORED ON THE PALLET FOR REFLIGHT AT MINIMAL COST
- BASED ON THE ABOVE CONCLUSIONS IT IS RECOMMENDED THAT A PHASE B STUDY BE INITIATED AND THAT SCALE BE PLACED ON THE MANIFEST FOR A 1991 FLIGHT

SCALE

Doppler Lidar Wind Measurement and the Earth Observing System



SCALE

APPENDIX
LASER SPACE QUALIFICATION STUDY

Spectra Technology

WINDVAN LASER STUDY

Submitted to
NASA MARSHALL

Submitted by
SPECTRA TECHNOLOGY, INC.

13 September 1985

C.11.338.01

WINDVAN LASER STUDY

Final Report

Contract #NAS8-36644

Submitted To

NASA/Marshall

George C. Marshall Space Flight Center

Marshall Flight Center, Alabama 35812

By

Spectra Technology, Inc.

2755 Northup Way

Bellevue, Washington 98004

13 September 1985

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TABLES

ILLUSTRATIONS

Section 1

INTRODUCTION

1.1 BACKGROUND

There is a growing concensus that global mapping of winds could have an enormous impact on both weather prediction and fundamental atmospheric science. Doppler lidar used from an earth orbiting platform appears to be an ideal approach for such measurements. The remote Doppler approach simultaneously provides excellent spatial and temporal coverage, combined with good spatial and velocity resolution.

The technical capability of the Doppler lidar approach has been demonstrated over the last five to ten years. Although Doppler measurements can in principle be made at any wavelength, the 9-11 μm band has been used for all existing Doppler wind velocity measurements. This wavelength region is attractive for its good atmospheric transmission and reasonablv large aerosol backscatter cross-section. This wavelength selection has also been strongly driven by the existence of the CO_2 laser, which is one of the oldest and best developed of all pulsed laser technologies.

Two developments in wind measurement account for much of our confidence in the Doppler lidar approach. A system developed by MSFC/Raytheon has produced a wide range of data from both airborne and ground based platforms. More recently, a mobile ground based system using pulsed TEA CO_2 technology has been developed at NOAA/WPL, originally using lasers developed by UTRC.

The MSFC system has shown the value of lidar deployment on highly mobile platforms for providing wide geographic coverage in a short time. However, because of the relatively low laser power available in the existing MSFC lidar, measurements can be made only at short ranges from the

aircraft. The corresponding NOAA lidar has demonstrated the capability of making high quality longrange measurements. The NOAA system routinely measures to and beyond the tropopause when operated from its ground based platform in midlatitude locations. SCALE can be viewed as a marriage of the mobility and long range capability o these two systems.

At the present time, the NOAA system is being upgraded to incorporate a new high power laser transmitter developed by Spectra Technology, Inc. The NOAA/STI laser system will increase the pulse energy by a factor of twenty, the pulse repetition rate by a factor of five, and the the velocity resolution by a factor of two, when compared with the existing capability. These transmitter capabilities are summarized in Table 1-1.

1.2 STUDY OBJECTIVES

This study has the goal of defining a CO_2 laser transmitter approach suited to SCALE requirements. Since the NOAA/STI WINDVAN transmitter meets the basic SCALE performance requirements (but in a ground based environment), our study has specifically addressed the adaptation of the existing WINDVAN design to the shuttle environment.

The study is intended to produce several results. First, we compare the needed performance (energy, coherence, repetition rate, size, weight, and reliability) of a conceptual SCALE transmitter with existing carbon dioxide laser technology. This comparison results in a statement of the anticipated performance of a SCALE transmitter, along with the time and cost for development of such a transmitter. A preliminary definition of STS interfaces results from this conceptual design. Finally, a qualitative assessment of the technical risk accompanying this development is given.

1.3 METHODOLOGY

The existing WINDVAN design has been evaluated subsystem by subsystem for compatibility both with SCALE performance requirements, and for

Table 1-1

NOAA WINDVAN SPECIFICATIONS

High Energy and Average Power	100 W (2 J @ 50 Hz)
Low Frequency Uncertainty	Chirp < 200 kHz Offset < 500 kHz
Wide Line Tunability	> 10 lines in 9 and 10 μm bands
Low Afterpulse	< 10^{-5} Watts after 8 μsec
Pulse Length Agility	> → 5 μsec
High Reliability	> 2 x 10^8 shots between maintenance cycles
Compactness	Fit within existing 1 Watt system space constraints
Fully Automated	Line changing, servo-lock, startup/shutdown, etc.
Wide Operating Range	0-14,000 ft., 18 to 30°C

compatibility with the shuttle bay environment. The study presumed that WINDVAN designs would be used with as little modification as possible to meet SCALE requirements.

In evaluating shuttle compatibility, we have assumed that it will be possible to use a Spacelab pallet and the accompanying electrical, thermal, and data support systems. This assumption has proven invaluable by defining well documented interfaces, and no incompatibility with the Spacelab infrastructure has been observed.

MSFC has provided extensive support to this study both by providing detailed discussion (and iteration) of SCALE transmitter performance requirements, and by transferring considerable detailed information concerning the STS bay environment. This cooperation is gratefully acknowledged.

1.4 SUMMARY OF CONCLUSIONS

The adaptation of the existing WINDVAN design to a one week shuttle flight appears to be entirely feasible. No new technology development is required for STS operation. The size, weight, and reliability, and efficiency of the existing WINDVAN system are largely compatible with SCALE requirements.

It should come as no surprise that an appreciable engineering development effort will be required to bring WINDVAN into compliance with STS bay operational requirements. Some repackaging is needed for compatibility with the vacuum and thermal environments. The largest changes will be required to ensure survival through launch and landing, mechanical, vibration and acoustic loads. Remote hands-off operability requires enhancement of command, control and optical alignment subsystems. Existing WINDVAN thermal management approaches which depend on convection must be upgraded for 0g operation.

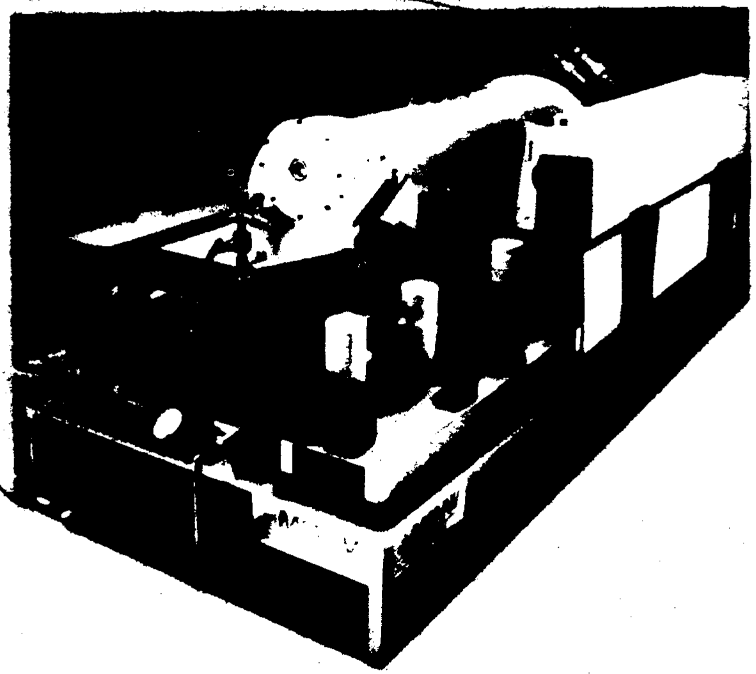
In summary, we believe that the existing WINDVAN design can be extended to STS operation through a predictable and manageable set of engineering revisions. The risk entailed in this program appears to be manageable, since no new technological development is required.

Figure 1-1 is a photograph of the WINDVAN transmitter. The similarities between it and the artist's concept of the SCALE transmitter are shown in Figure 1-2.

NOAA "WINDVAN" CO_2 LIDAR UNIT

MOBILE TRAILER

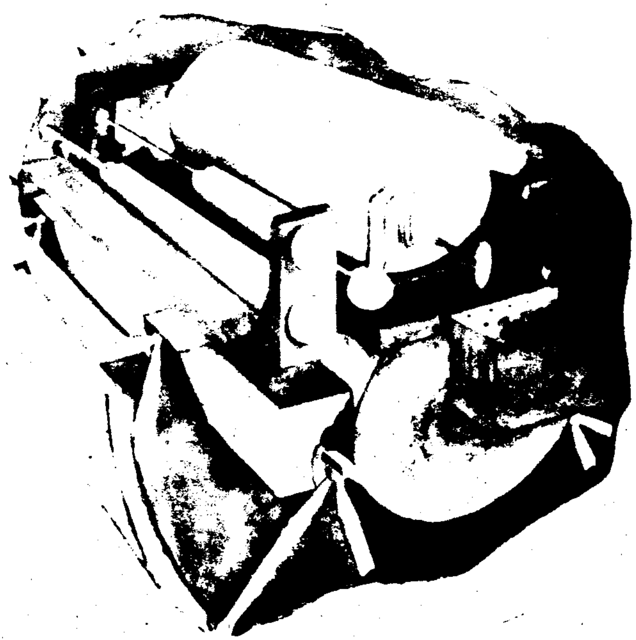
LASER TRANSMITTER

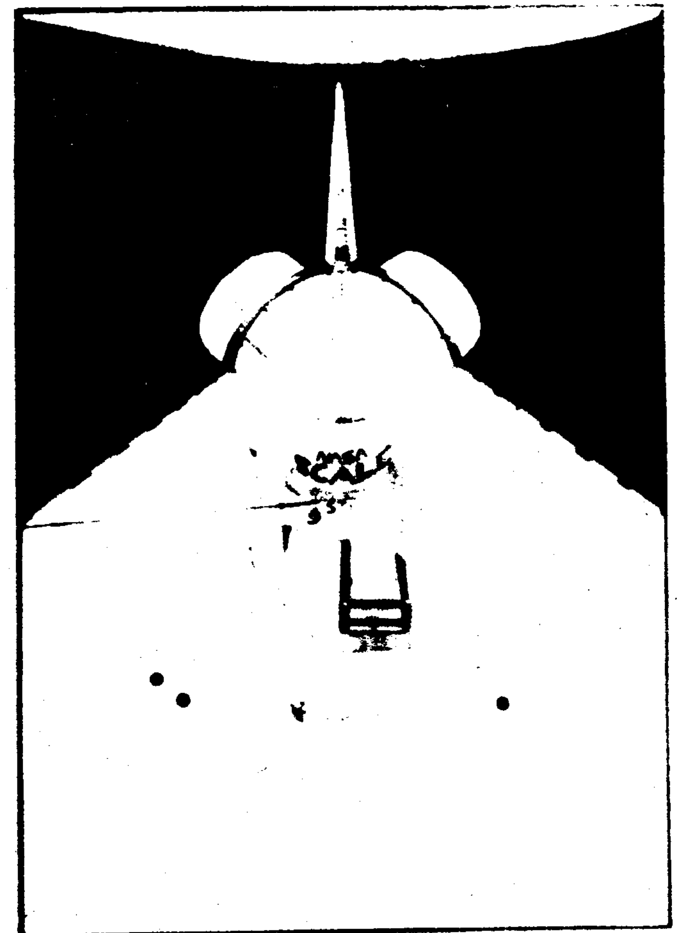


Spectra Technology

NASA SHUTTLE COHERENT ATMOSPHERIC LIDAR EXPERIMENT (SCALE)

LASER TRANSMITTER





ORBITER PAYLOAD

ORIGINAL PAGE IS
OF POOR QUALITY

Spectra Technology

Section 2

SCALE TRANSMITTER CONCEPT

2.1 SYSTEM OVERVIEW

The specifications for the SCALE transmitter listed in Table 2-1. The lidar Laser System contains both pulsed transmitter and cw local oscillator lasers. A third laser, another cw laser referred to as the injection oscillator, serves as a frequency reference for the entire systems. Figure 2-1 is a conceptual layout of the entire system. Schematically the SCALE system is identical to the WINDVAN.

The injection oscillator and local oscillator for the WINDVAN are both commercial, low pressure longitudinal discharge cw lasers made by Ultra-Lasertech, of Canada. All three lasers have diffraction gratings in their cavities to force operation on a single rotational line of CO_2. Hardened versions of these lasers are available which meet military specifications from vendors such as Hughes Aircraft.

The injection oscillator (IO) is locked to CO_2 line center by searching for maximum intensity vs cavity length. The cavity length is modulated ("dithered") with an amplitude equivalent to 0.5-1 MHz. The laser output is sampled by a HgCdTe detector. The dc length is adjusted by a standard linear hill climbing servo approach which finds the point of zero derivative. This fixed frequency (except for the dither) signal effectively serves as the reference for the entire system.

The local oscillator is offset locked with respect to the injection oscillator, using another HgCdTe detector and a frequency counting based loop. The effect of the IO dither is eliminated from this loop by always counting the beat frequency for entire dither period, so that the frequency variation averages to zero over any given measurement. The beam from the

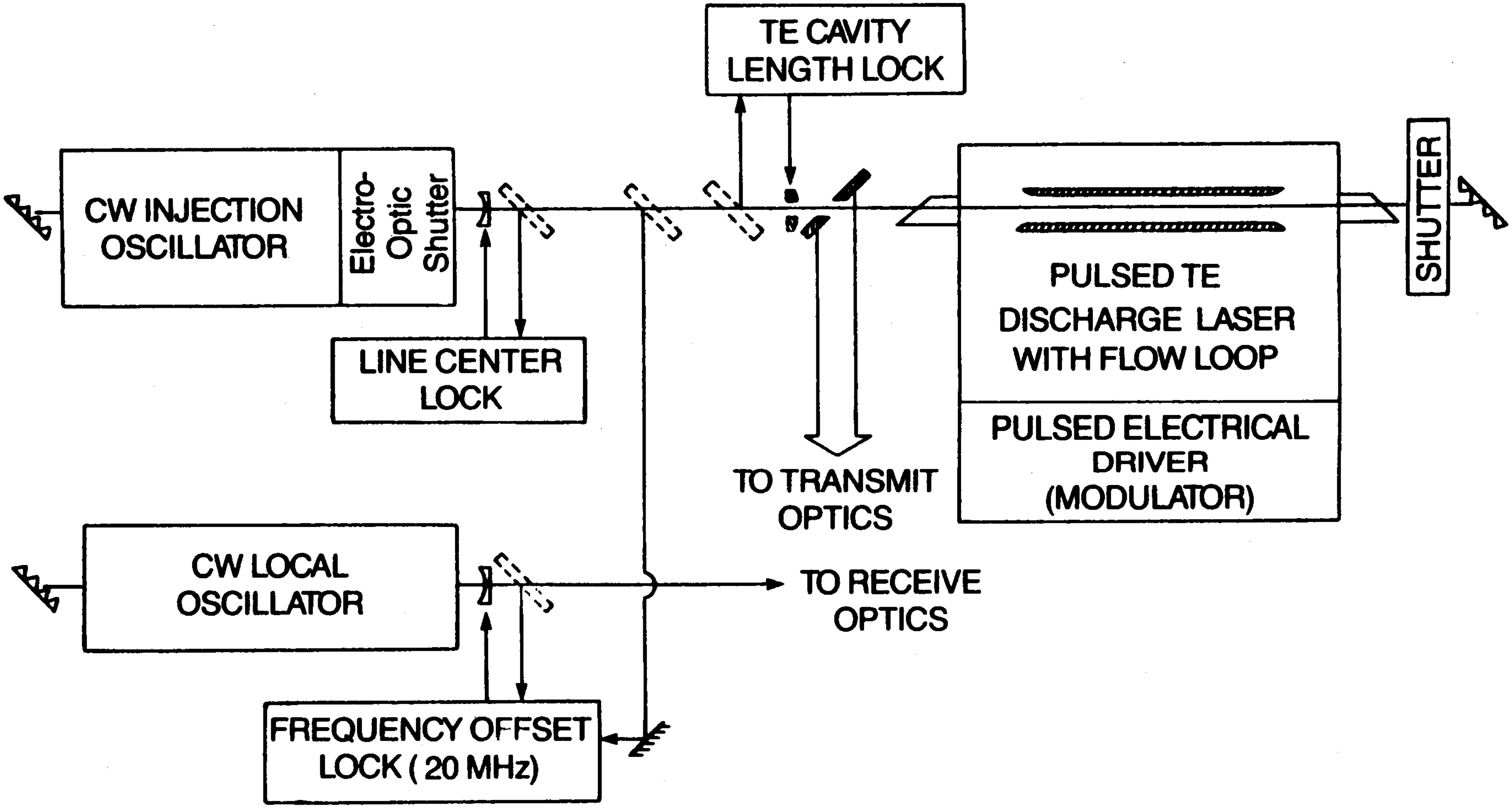
Table 2-1

SCALE TRANSMITTER SUBSYSTEM PRELIMINARY REQUIREMENTS

LASER

- 2 J Pulse Energy
- 50 Hz Repetition Rate *
- 4 µs Pulse Duration
- 5% Wall Plug Efficiency
- Isotopic Gas (9.11 µm)
- 10^7 Shot Lifetime
- Nonrecycling Operation

* Reducing Rep Rate to 25 Hz May Best Fit Overall Mission Constraints



83 07207

Figure 2-1. Conceptual Design for High Average Power Lidar Upgrade

local oscillator is delivered to the edge of the table for use in the interferometer, and has no other role in the laser system.

The heart of the system is of course the pulse TE laser. This device is a large aperture, low pressure self-sustained discharge device, which is described in Section 3.1. The TE laser uses an unstable resonator, which is described in Section 3.5. The TE laser resonator is injected with light from the IO, forcing single longitudinal mode operation. For injection to be successful, the injection frequency must agree with a longitudinal mode frequency of the transmitter resonator. This resonant condition is enforced by a servo loop on the power oscillator (PO) cavity length. More detail on this process is given in Section 3.5

The system is operated by an integrated computer control system, which is interfaced to all relevant external sensors and actuators,and to the servo loop electronics. Our approach of integrating all functions in a single unit has led to a number of advantages. Using this approach it is straightforward to allow computer control of servo loop parameters, which, in turn, allows easy implementation of automatic locking of the servo loops. It also allows all time-dependent signals to be derived from a single clock, so that synchronism of various events is easily ensured.

2.2 FUNCTIONAL FLOW

As a prerequisite to an evaluation of any system as complex as the SCALE transmitter, division into subunits according to function must be performed. Figure 2-2 shows the five major transmitter subsystems and how they interact with one another. Two central boxes, the mechanical and electrical subsystems, contain the components of the TEA laser. The other boxes include the gas makeup system, the optical/structural system, the thermal system and the data handling and control system. The subsystems themselves as well as the components within the subsystems may then be isolated and evaluated in terms of suitability for meeting the design goals.

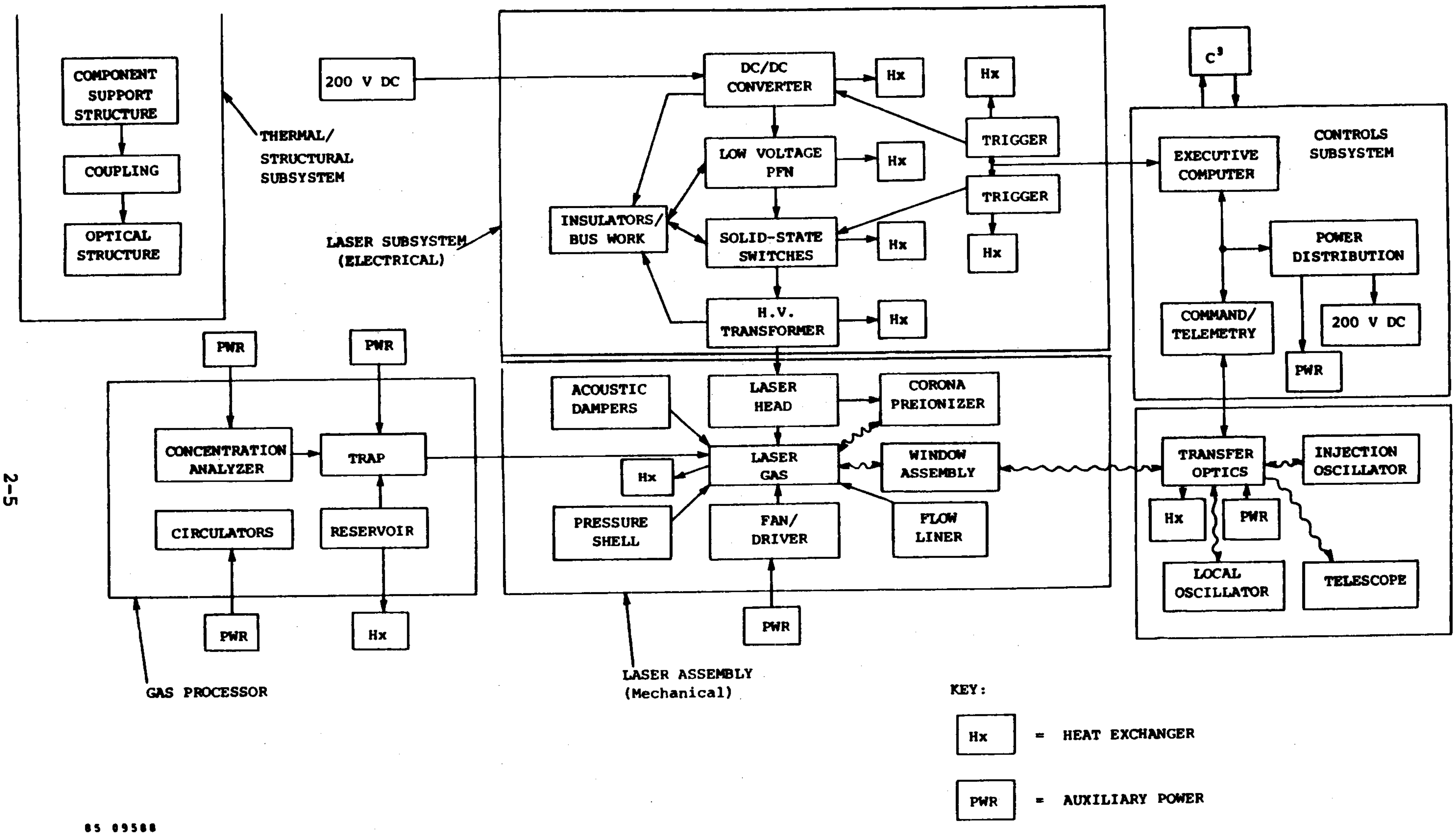


Figure 2-2. Functional Flow Diagram for NASA CO_2

2.3 RISK ASSESSMENT

To evaluate risk, an assessment formalism is employed which assigns numerical factors to the components in three categories: the level of development to which the item has been carried, the amount of supporting analysis which is available and the degree to which the component is critical to the success of the mission. The risk score is the product of the three values. Table 2-2 illustrates this rating system. Scores may be used to establish the readiness of individual components. They may also be summed to determine the overall readiness of the subsystem. This approach is used for each subsystem to evaluate the potential of the transmitter system to perform the SCALE mission. The results are tabulated for each of the subsystems and are used to indicate where resources might be spent on further development in order to insure success.

2.4 INTERFACE

The primary output of this study is a determination of transmitter feasibility for the SCALE mission. This is in turn dependent on the ability of the transmitter to utilize onboard services of the shuttle. To simplify this determination the extensive documentation provided for the ESA Spacelab pallet was used to establish the interface requirements and to configure the payload in the cargo bay. Results for each laser subsystem are tabulated in terms of the demands placed on the shuttle resources including power, weight, volume, heat rejection, and data.

Table 2-2

NUMERICAL FACTORS FOR RISK ASSESSMENT

CATEGORY	NATURE OF DEVELOPMENT		CATEGORY	SUPPORTING ANALYSIS/DATA		CATEGORY	FUNCTIONAL CRITICALITY		RISK PRODUCT
	SUBSET	VALUE		SUBSET	VALUE		SUBSET	VALUE	
1	RESEARCH	16	1	NONE	4	1	HIGH	3	
2	FEASIBILITY DEMONSTATION	8	2	MINIMAL	3	2	MODERATE	2	
3	ENG. DEVELOP. FOR SYS. TEST	4	3	PARTIAL	2	3	LOW	1	
4	ENG. FOR SPACE DESIGN	2	4	FULL	1				
5	SPACE QUALIFICATION	1							

Section 3

LASER TRANSMITTER SUBSYSTEMS

Table 3.1-1 lists the subsystems of the SCALE transmitter along with the major components. In the sections which follow, the functins of each of the subsystems is discussed and an assessment of the radiness of each is presented.

3.1 LASER MECHANICAL

The pulsed transmitter is a discharge pumped transverse discharge device. The dimensions of the discharge are 4X4X60 cm. These dimensions were chosen to minimize chirp, and the geometry of the device is quite different from a 2 J laser not designed for lidar application. The device is designed to operate at a total pressure of approximately 0.5 atm.

The discharge is preionized by a "corona" type UV source. Preionization is required to allow an initial small level of conductivity to support smooth initiation of the main discharge. Attempts to operate the discharge without preionization result in nothing but a single concentrated arc somewhere between the electrodes. This preionization source is simple, compact, and so far as proven reasonably reliable. The corona source is a large area insulate conductor located just behind one of the electrodes, which is made of screen to allow passage of the UV radiation. UV is generated by the capacitive charging of the insulator surface across a small gas gap.

The corona bar is pulsed using a passive circuit approach. Essentially, the corona is driven during the leading edge of the main discharge pulse while the instantaneous voltage betweeen the screen electrode and te corona bar is changing quickly. Separate active corona bar drivers were tried during the development of the laser, and did not give results superior to the simple passive approach.

Table 3.1-1

SCALE LASER TRANSMITTER SUBSYSTEMS AND COMPONENTS

SUBSYSTEM	COMPONENT
Laser (Mechanical)	Transverse Fan
	Bearing
	Fan Motor
	Magnetic Coupling
	Drive Coupling
	Flow Liner
	Ground Electrode
	HV Electrode
	Pressure Shell
Power Modulator	DC/DC Converter
	Low Voltage PFN
	Solid State Switch
	High Voltage Transformer
	Trigger Assembly
Thermal	Freon Pump Package
	Experiment Heat Exchanger
	Laser Heat Exchanger
	Modulator Pump
	Modulator Flow Ducting
Gas Regeneration	Blower
	Regenerative HX
	Catalyst Container
	Catalyst Charge
	Catalyst Heater
	Filter
Optical/Structural	Optical Table
	Cavity Space Frame
	Infrared Detectors
	Oscillators
	Servo Sub-Bench
	TE Laser Resonator
	Acoustic Shell
Data and Control	Telemetry Interface
	Supervisory Computer
	Control Electronics and Sensors

The discharge is pulsed by a circuit (the "modulator", see Section 3.2) which applies about 30 kV to the electrodes for a period of 500 nsec. The peak discharge current is in excess of 3000 amps. Total energy deposited in the gas by the pulser is about 40 J.

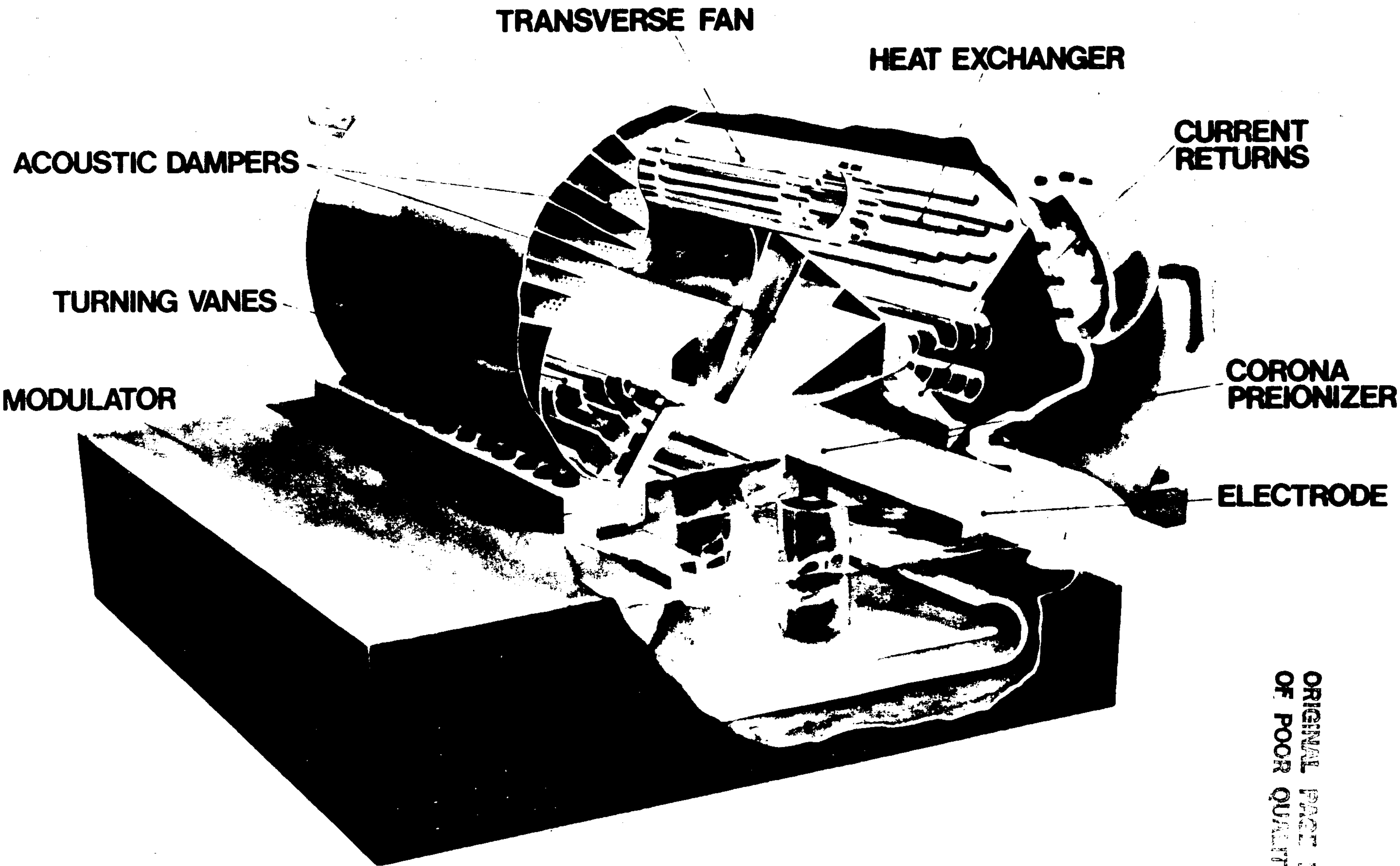
Gas is flowed through the discharge volume at a rate sufficient to support 50 Hz operation. This requires a minimum of approximately 2 gas exchanges per 20 msec. The cylindrical shell of the TE containment vessel essentially forms the outer wall of the flow duct as well. The inner wall consists of the center section, which does double duty as the ground electrode. A series of vanes connects the ground electrode to the main flange to provide a low impedance electrical return path while simultaneously causing minimum perturbation of the gas flow.

The center section of the flow loop is divided into compartments which form acoustic dampers. The entrance port for the dampers is a screened slot which runs the full length of the discharge region, and is located just downstream from the discharge. These dampers function to rapidly dissipate high frequency pressure fluctuations that result from the impulsive heating of the gas in the discharge region after each pulse.

3.1.1 WINDVAN and SCALE Laser Heads Compared

The similarities and changes in the laser mechanical features in going from the WINDVAN Configuration to the upgraded Transmitter can be seen by comparing the cutaway view of the WV shown in Figure 3.1-1 and the wire frame view of the SCALE subsystem shown Figure 3.1-2.

The laser head and compact flow loop assembly are almost identical in each subsystem. This is important in achieving maximum carryover since the discharge and flow technology incorporated in this component is responsible for most of the success of the WV design and represents the largest contribution to the development cost of that device. The most significant difference in the two are in the containers which house the electrical components that drive the laser.



MSNW · NOAA CO_2 LIDAR LASER

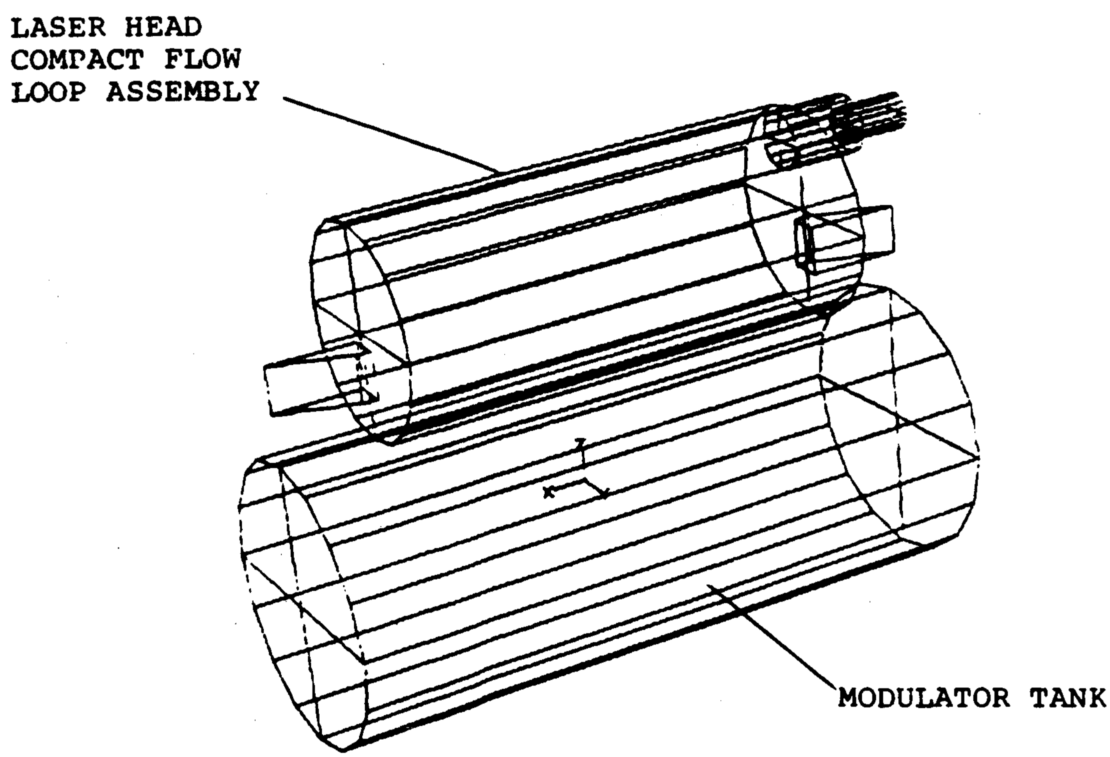


Figure 3.1-2. SCALE Laser Mechanical Configuration

The WINDVAN power supply and modulator are packaged in separate, rectangular, approximately equal volume tanks one of which is shown in Figure 3.1-1. In the SCALE design these components can be housed in a single cylindrical enclosure with a volume as indicated in Figure 3.1-2. The primary mechanical requirements imposed by the mission on the subsystem are the need to maintain the pressure and vacuum integrity and the need to withstand the vibration and loads during launch and maneuver. The sealed, domed end containers in the SCALE design satisfy the former and the packaging of the power supply and modulator discussed in the below in the laser electrical section satisfies the latter.

3.1.2 Criticalities, Mechanical Requirements

Table 3.1-2 gives the list of mechanical components shown in relation to the mission and shuttle design environment. Particular sensitivity of a component is denoted by a dot in the matrix and calls attention to the need for a data base and appropriate testing to certify the design approach selected.

3.1.3 Mechanical Risks

As can be seen from Table 3.1-3, the magnitude of the risk scores for the components of the mechanical system indicate that there are no serious issues associated with hardening the system for space. This is because all of the components have a space rated equivalent or a design data base from which space qualified version can be engineered.

Since the laser mechanical system is composed of an array of parts in a relatively high-Q configuration, a mass model of the system will reveal resonances in the bandwidth of the launch vibration spectrum. A modal analysis test to verify these predictions would be expected as part of the normal qualification process.

Table 3.1-2

CRITICALITY OF EQUIPMENT TO DESIGN ENVIRONMENTS

DESIGN ENVIRONMENTS

SUBSYSTEM: Laser (Mechanical) ITEM	THERMAL VACUUM	THERMAL CYCLE	SINE VIBRATION	RANDOM VIBRATION	ACOUSTIC NOISE	PYROSHOCK	ACCELERATION	HUMIDITY	PRESSURE	LEAKAGE	CHEMICAL CORROSION	SHOCK VIBRATION	FLOW	HIGH VOLTAGE	EMP
1 FAN/DRIVE	o	o	o	o		o	o				o	o	o		
Transverse Fan			o	o		o	o				o				
Bearing/Ferro Labyrinth Seal			o	o		o	o				o	o	o		
Drive Shaft Coupling	o	o									o				
Fan Motor			o	o		o	o					o			
Magnetic Coupling			o	o		o	o					o			
2 FLOW LINER			o	o	o	o					o		o		
3 LASER HEAD (MECH.)	o	o	o	o	o	o	o		o		o	o	o		
Ground Electrode											o		o		
HV Electrode		o	o	o		o	o				o	o			
Laser Head Flange	o	o							o	o	o				
4 PRESSURE SHELL	o	o							o	o	o		o		
Outer Shell	o	o							o	o	o		o		
End Flanges	o	o							o	o	o		o		
5 WINDOW ASSEMBLY															
Gas Circulator	o	o	o	o		o	o		o	o	o	o	o		
6 HEAT EXCHANGER			o	o		o	o			o	o	o	o		
7 CORONA X-RAY PREIONIZER WINDOW	o	o			o				o	o	o		o		

LASER MECHANICAL COMPONENT RISK ASSESSMENT

NATURE OF DEVELOPMENT		SUPPORTING ANALYSIS/DATA		FUNCTIONAL CRITICALITY		TOTAL
ITEM Fan Drive	VALUE		VALUE		VALUE	
CATEGORY 4	2	CATEGORY 4	1	CATEGORY 1	3	6
ITEM Flow Liner						
CATEGORY 4	2	4	1	1	3	6
ITEM Laser Head						
CATEGORY 4	2	4	1	1	3	6
ITEM Pressure Shell						
CATEGORY 4	2	4	1	1	3	6
ITEM Window Assembly						
CATEGORY 4	2	4	1	1	3	6
ITEM Heat Exchanger						
CATEGORY 4	2	4	1	1	3	6
ITEM Preionizer						
CATEGORY 3	4	3	2	1	3	24

3.1.4 Mechanical Requirements Summary

A summary of the weights, volumes and power requirement is given for each of the components in the mechanical system in Table 3.1-4. The weight of the pressure shell, the heaviest component, includes the weight of the electrical components and insulating fluid contained within.

3.2 SCALE POWER MODULATOR

The purpose of the SCALE power modulator is to condition raw dc power and make it useful for operating the laser. Figure 3.2-1 shows the overall power modulator block diagram. A low voltage dc power bus feeds a dc/dc converter that charges a low voltage pulse-forming network (PFN). A solid-state switch then switches the energy stored on the PFN into the primary of the high voltage pulse transformer which, in turn, energizes the laserhead. The executive computer controls the trigger assemblies for optimum circuit performance and efficiency.

3.2.1 Laser Electrical System

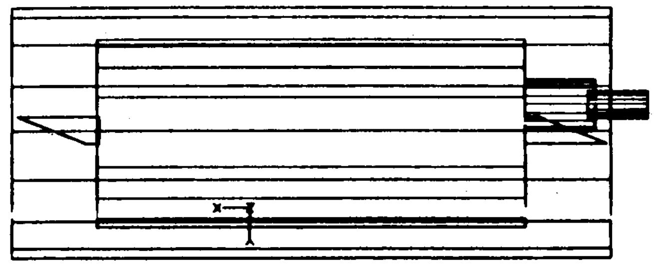
Figure 3.2-2 illustrates major components in the power modulator circuit topology and their associated timing waveforms. The dc/dc converter initially takes the input power bus voltage (approximately 200 V) and charges the PFN to 3 kV in about 1 ms. Once this is completed, the converter is turned off and the solid-state switch is fired, which introduces a 30 kV pulse across the laserhead. This causes the head avalanche and breakdown, and the laser gas then supports a 15 kV, 800 A power pulse for approximately 3 μs. The PFN determines both the pulse shape and pulse duration of the power pulse.

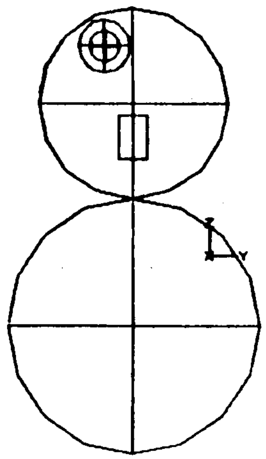
The solid-state switch identified for the modulator is the Westinghouse RBDT (Reverse Blocking Diode Thyristor), which has seen extensive field service in FAA radar systems.(1) The switching requirements for SCALE have been matched fairly closely to published radar

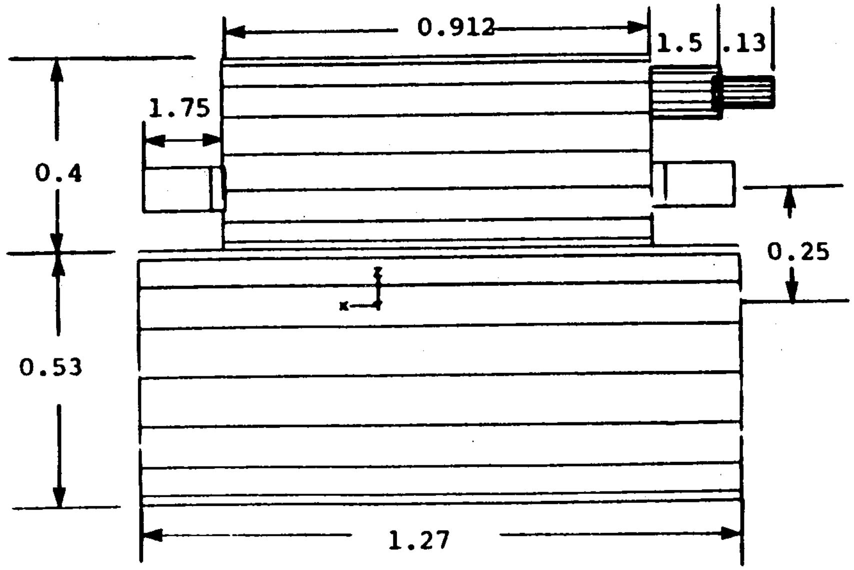
Table 3.1-4

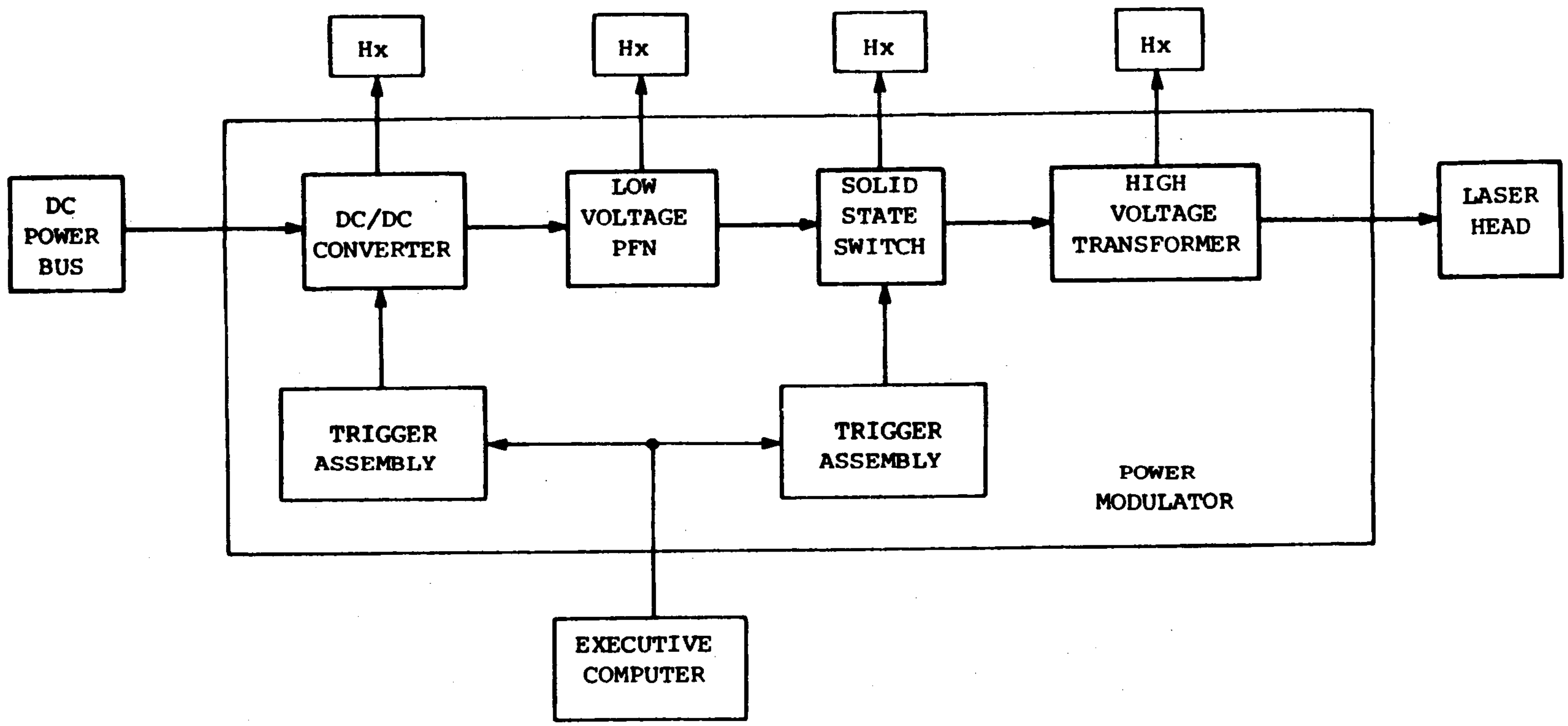
LASER (MECHANICAL) REQUIREMENTS SUMMARY

COMPONENT	POWER (W)	WEIGHT (kG)	VOLUME (kG)
1 Fan/Driver	75	5	0.030
2 Flow Liner	--	7	--
3 Laser Head/ Feedthrough	--	10	0.030
4 Pressure Shell	--	80	0.94
5 Window Assembly	--	5	0.60
6 Heat Exchanger	--	8	--
7 Corona Preionizer	--	10	0.015









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- Power Modulator all Solid State.
- Laserhead Driven by a High Voltage Transformer Which Allows Electronics to Operate at Relatively Low Voltages.
- Except at the Laserhead, Voltages in Modulator Tank will not Exceed 3 kV.
- Solid-State Switches are RBDTs.

Figure 3.2-1. Power Modulator Block Diagram

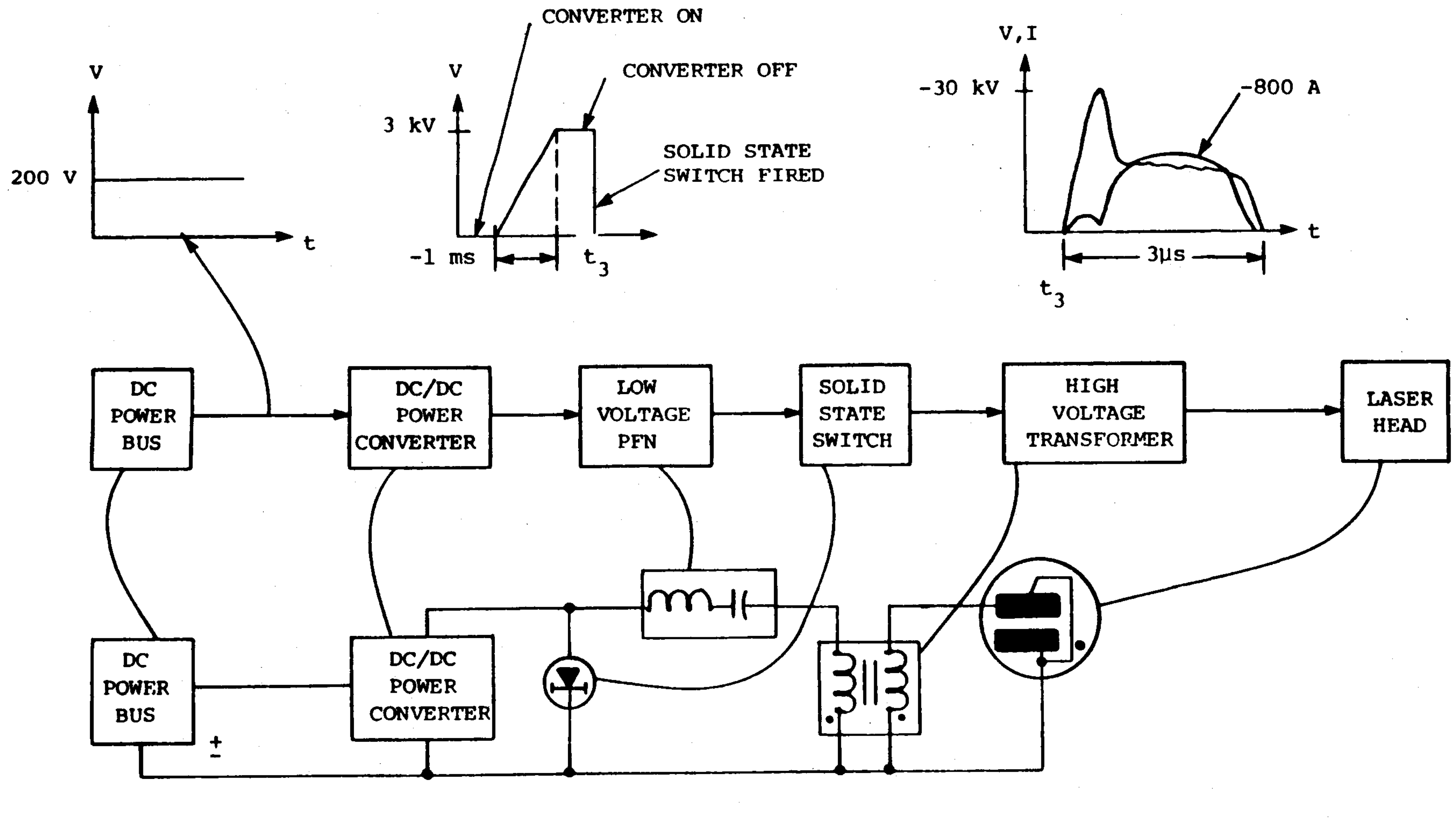

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Figure 3.2-2. Power Modulator Circuit Topology

requirements, so we see no real risk in incorporating the RBDTs into the laser system. The high voltage transformer technology is well understood and should pose no special problems.

An efficiency flowchart for the SCALE power modulator is shown in Figure 3.2-3. Working back from the laserhead, which requires 1750 W of power at 50 Hz, we have estimated the component efficiencies to be:

COMPONENT	**EFFICIENCY**
High Voltage Transformer	90%
Solid-state Switch	90%
PFN	95%
DC/DC Converter	90%
TOTAL Modulator Efficiency	**68%**

For a 68 percent efficient modulator, power requirements at the input dc power bus are 2600 W at 50 Hz, and 750 W must be removed by active cooling.

3.2.2 Comparison of WINDVAN and SCALE

The SCALE power modulator differs from the existing WINDVAN modulator in that SCALE will use solid-state switches whereas WINDVAN uses thyratrons. (Thyratrons are low pressure gas switches that require a substantial amount of auxiliary heater power.) Table 3.2-1 compares the two modulators. The principal advantages of SCALE over WINDVAN are overall system efficiency due to reduced auxiliary power requirements and size and weight. The proposed dc/dc converter for SCALE is substantially smaller and lighter than the WINDVAN power supply. We expect the SCALE modulator to require one-third less power and to be one-third smaller and lighter than WINDVAN. Figure 3.2-4 shows an overall drawing of the SCALE laserhead/modulator assembly, and Table 3.2-2 tabulates the power modulator requirements on the spacecraft.

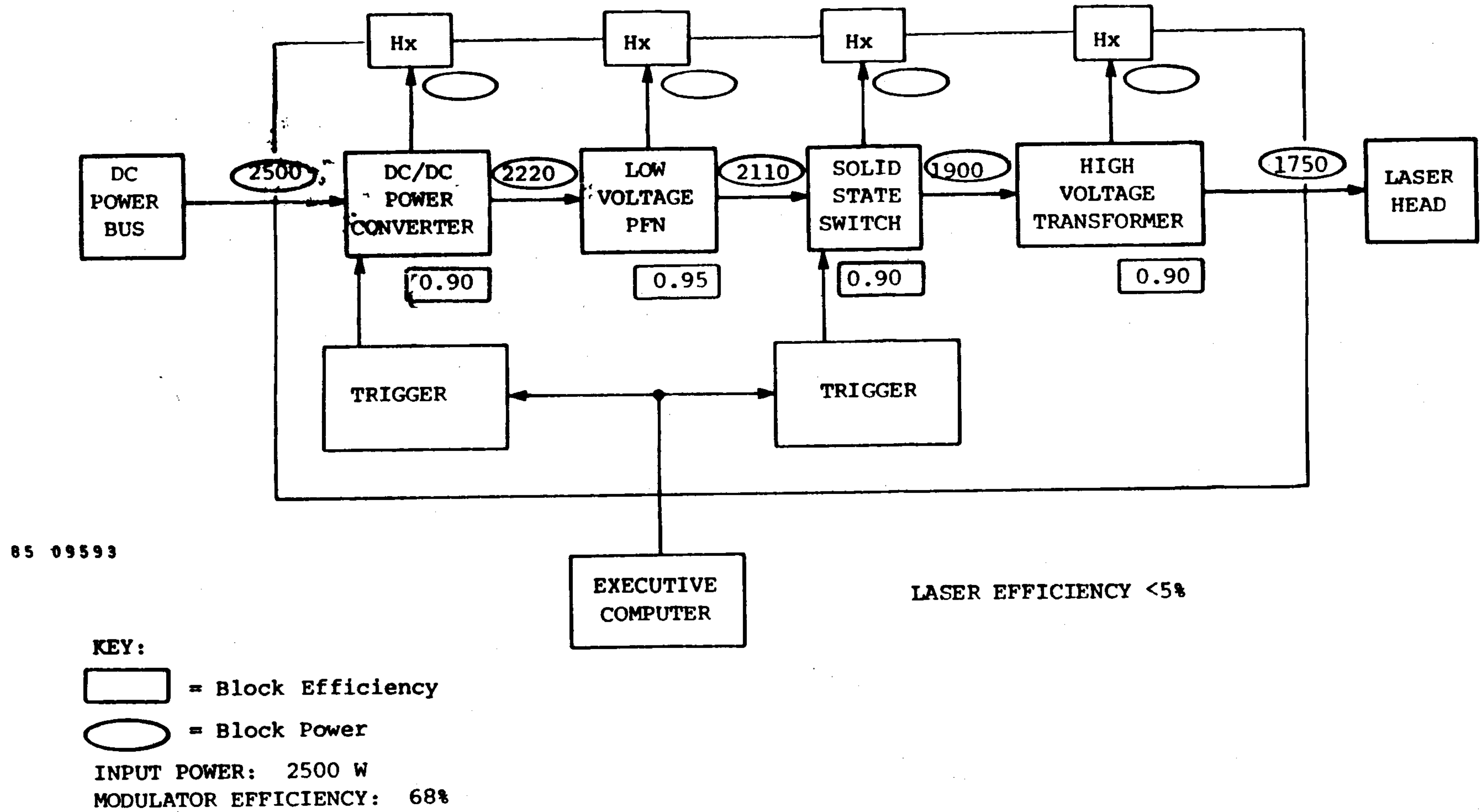

Figure 3.2-3. Power Modulator Efficiency

Table 3.2-1

POWER MODULATOR COMPARISONS

CATEGORY	**NASA CO_2**	**WINDVAN**
Switches	Solid-State RBDTs	2 Thyratrons
Transformers	1	1
Charging Inductors	-	1
Power Supply	DC/DC Converter	Standard Lab Supply
Trigger Assemblies	2	2
PFN	1	1
Auxiliary Heater Power	-	800 W
Overall Power Requirements @ 50 Hz	2.5 kVA	3.3 kVA
Volume	1.4 m^3	0.2 m^3
Weight (with oil)	1500 lb_m	2200 lb_m

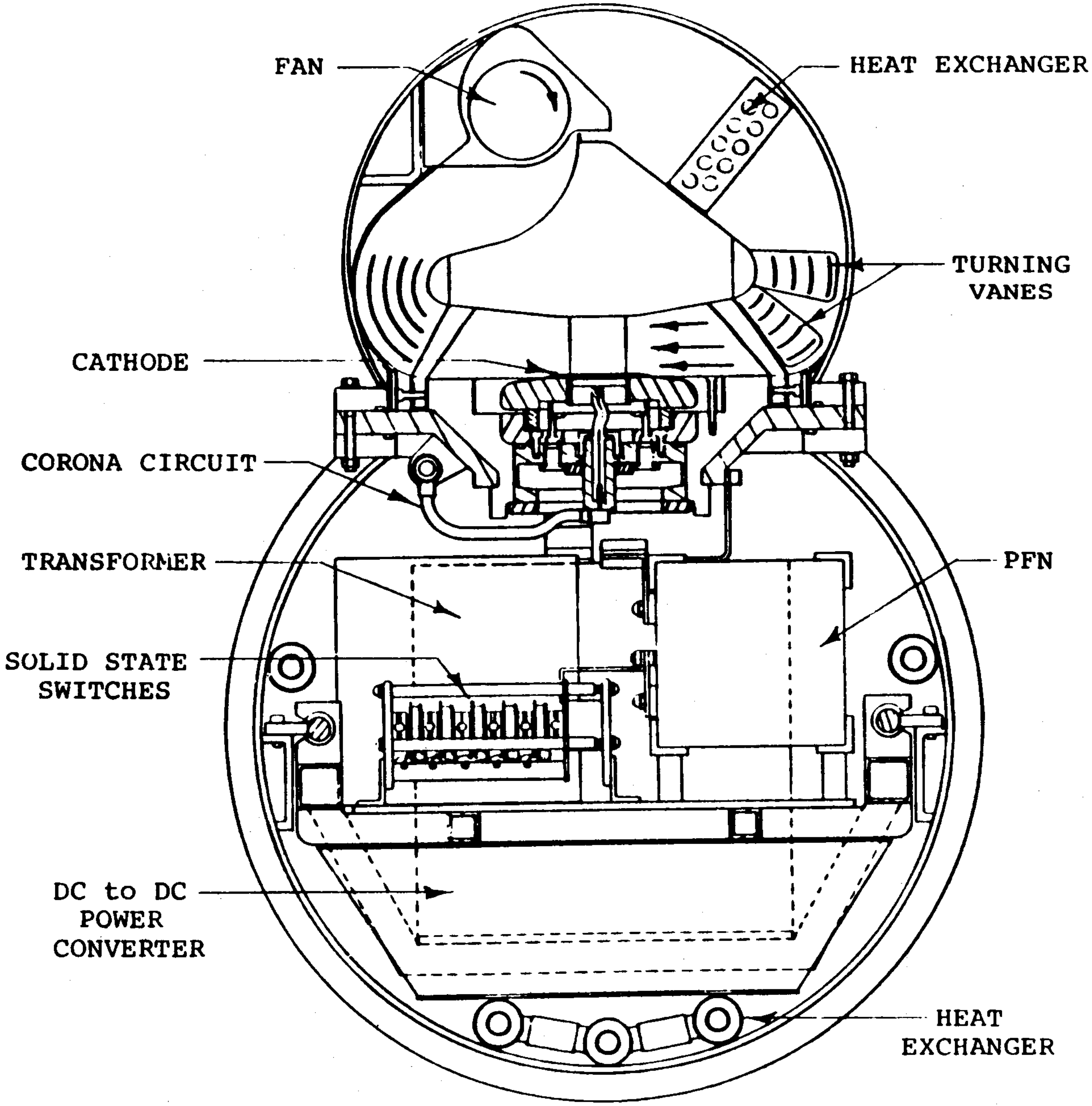

Figure 3.2-4. Laser Head/Modulator

<u>LASER</u>

WEIGHT-≈495 lbs
VOLUME-≈4.4 ft^3
(16" dia x 38" lg)

<u>MODULATOR</u>

WEIGHT-≈1000 lbs.
VOLUME-≈8.5 ft^3
(22" dia x 38" lg)

Table 3.2-2

POWER MODULATOR SPACECRAFT REQUIREMENTS

Input Power	2500 W at 200 VDC
Output Power (to laserhead)	1750 W
Power Dissipated in Modulator	750 W
Modulator Volume	0.3 m^3
Modulator Weight	455 kG

3.2.3 Risk Assessment

Even though the SCALE modulator is smaller and more efficient than WINDVAN, it should offer no more risk than the WINDVAN approach. Table 3.2-3 gives the sensitivity of the power modulator to the design environment. Table 3.2-4 shows the risk associated with the modulator components. Table 3.2-5 gives the risk assessment for the SCALE modulator. The solid-state switch in SCALE poses a certain amount of risk in implementing the system; however, because RBDTs consume 800 W less power and are less sensitive to vibration and shock damage than are thyratrons and because thyratrons have not been space-qualified, we have rated the risk of thyratrons and RBDTs as being the same. Other circuit aspects of the two modulators are essentially identical.

The power modulator will be subjected to various types of shocks and vibrations during its mission life. Possible causes of failure are listed in Table 3.2-5, along with modulator sections that are exposed to these dangers. The detailed SCALE design must address the different operating environments; however, a major portion of these design problems have been successfully addressed by WINDVAN, and we feel confident that the upgraded SCALE modulator design will satisfy all requirements placed on it.

3.3 LASER THERMAL

The laser thermal system must insure that the temperatures of the laser medium, the laser modulator and the peripheral equipment on the pallet are maintained within the desired limits.

Table 3.2-3

CRITICALITY OF EQUIPMENT TO DESIGN ENVIRONMENT

SUBSYSTEM:
Power Modulator

ITEM	THERMAL VACUUM	THERMAL CYCLE	SINE VIBRATION	RANDOM VIBRATION	ACOUSTIC NOISE	PYROSHOCK	ACCELERATION	HUMIDITY	PRESSURE	LEAKAGE	CHEMICAL CORROSION	SHOCK VIBRATION	FLOW	HIGH VOLTAGE	EMP
DC/DC Converter		o	o	o		o	o				o	o		o	o
Low Voltage PFN		o	o	o		o	o			o	o	o		o	
Solid State Switch		o	o	o		o	o				o	o		o	o
High Voltage Transformer		o	o	o		o	o				o	o		o	
Trigger Assemblies		o	o	o		o	o				o	o		o	o

Table 3.2-4

POWER MODULATOR COMPONENT RISK ASSESSMENT

SUBSYSTEM: Power Modulator

NATURE OF DEVELOPMENT		SUPPORTING ANALYSIS/DATA		FUNCTIONAL CRITICALITY		TOTAL
ITEM DC/DC CONVERTER	VALUE		VALUE		VALUE	
CATEGORY 3	4	CATEGORY 3	2	CATEGORY 1	3	24
ITEM LOW VOLTAGE PFN						
CATEGORY 4	2	4	1	1	3	6
ITEM SOLID STATE SWITCH						
CATEGORY 3	4	3	2	1	3	24
ITEM HIGH VOLTAGE TRANSFORMER						
CATEGORY 4	2	4	1	1	3	6
ITEM TRIGGER ASSEMBLIES						
CATEGORY 4	2	4	1	1	3	6
ITEM						
CATEGORY						
ITEM						
CATEGORY						

Table 3.2-5

POWER MODULATOR RISK/ASSESSMENT

CATEGORY	NASA CO_2	WINDVAN
DC/DC Converter	24	24
PFN	6	6
Switches	24	24
High Voltage Transformer	6	6
Trigger Assemblies	6	6
	36	36

Since risk scores are identical, focus on solid-state modulator approach. Reasons for this:

- o Solid-state approach consumes 800 W less power
- o Solid-state approach less sensitive to vibrational/shock damage
- o Packaging will be smaller than for thyratron version
- o Thyratrons have not been space-qualified

3.3.1 Thermal Requirements

Table 3.3-1 lists the important temperatures and heat fluxes for the transmitter. The effect of temperature on the laser output is shown in Figure 3.3-1. A temperature ten degrees above the maximum coolant inlet temperature can result in a 15 percent decrease in transmitter efficiency. To insure that this temperature is minimized the laser head and flow loop are located nearest to the coolant inlet port in the payload flow loop.

3.3.2 Thermal System

Figure 3.3-2 showns the thermal schematic of a system. The system consists of three flow loops the primary one being the orbiter cargo bay loop which addresses the pallet as well as all the other actively cooled equipment installed in the bay. The Experimental Equipment loop,addresses the apparatus requiring direct liquid cooling. The interface between the two is the Payload loop which provides the isolation necessary for safety and for convenience during preflight testing. The Payload loop also addresses equipment which is normally part of the ESA pallet including the igloo and the pallet cold plates. The interface between the Payload loop and the experiment is through the Experiment heat exchanger. This component is normally used on the ESA module but may be adapted for use on the pallet thus permitting the use of a space qualified unit at this important interface. The other important item that can be directly utilized from the list of space qualified equipment is the freon pump package. Two identical units are indicated in Figure 3.3-2. The unit is shown in detail in Figure 3.3-3. The capacity of this unit matches well with the 3150w heat load in the experiment loop.

Equipment for the thermal system can thus be divided into two major groups; the first includes that of a general purpose nature that can be selected from an array of existing space qualified equipment and as such can be expected to meet most or all of the mission requirements without modification. The second group which includes the experiment specific

Table 3.3-1

TRANSMITTER TEMPERATURS AND HEAT FLUXES

Heat Deposited Flow Loop From Discharge		1650 W
Heat Deposited in Modulator		750 W
Auxiliary Payload Heat Load		750 W
	Total	3150 W
Maximum Orbiter Bay Coolant Inlet Temperature		38 °C

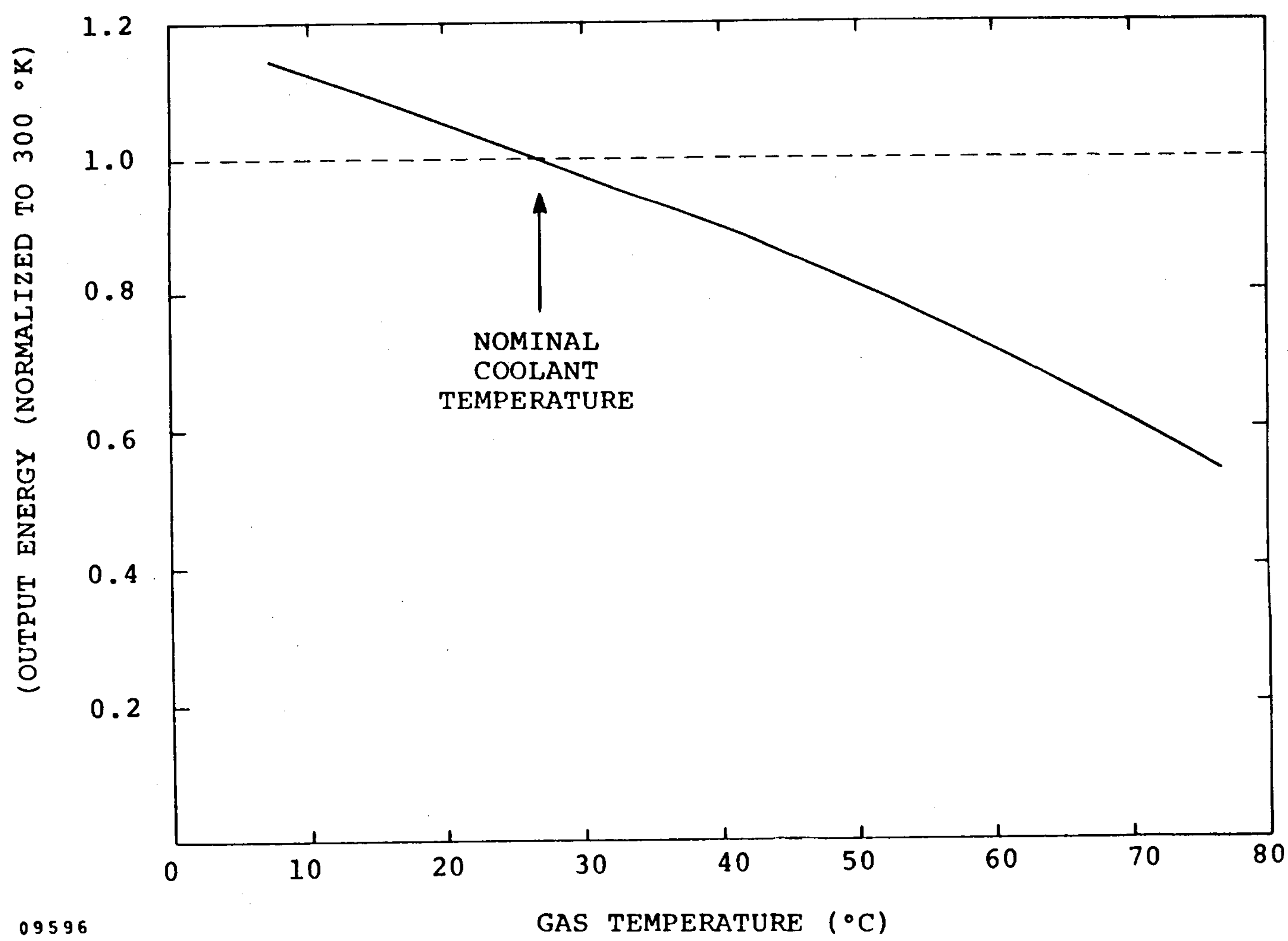

Figure 3.3-1. Effect of Temperature on Laser Output.

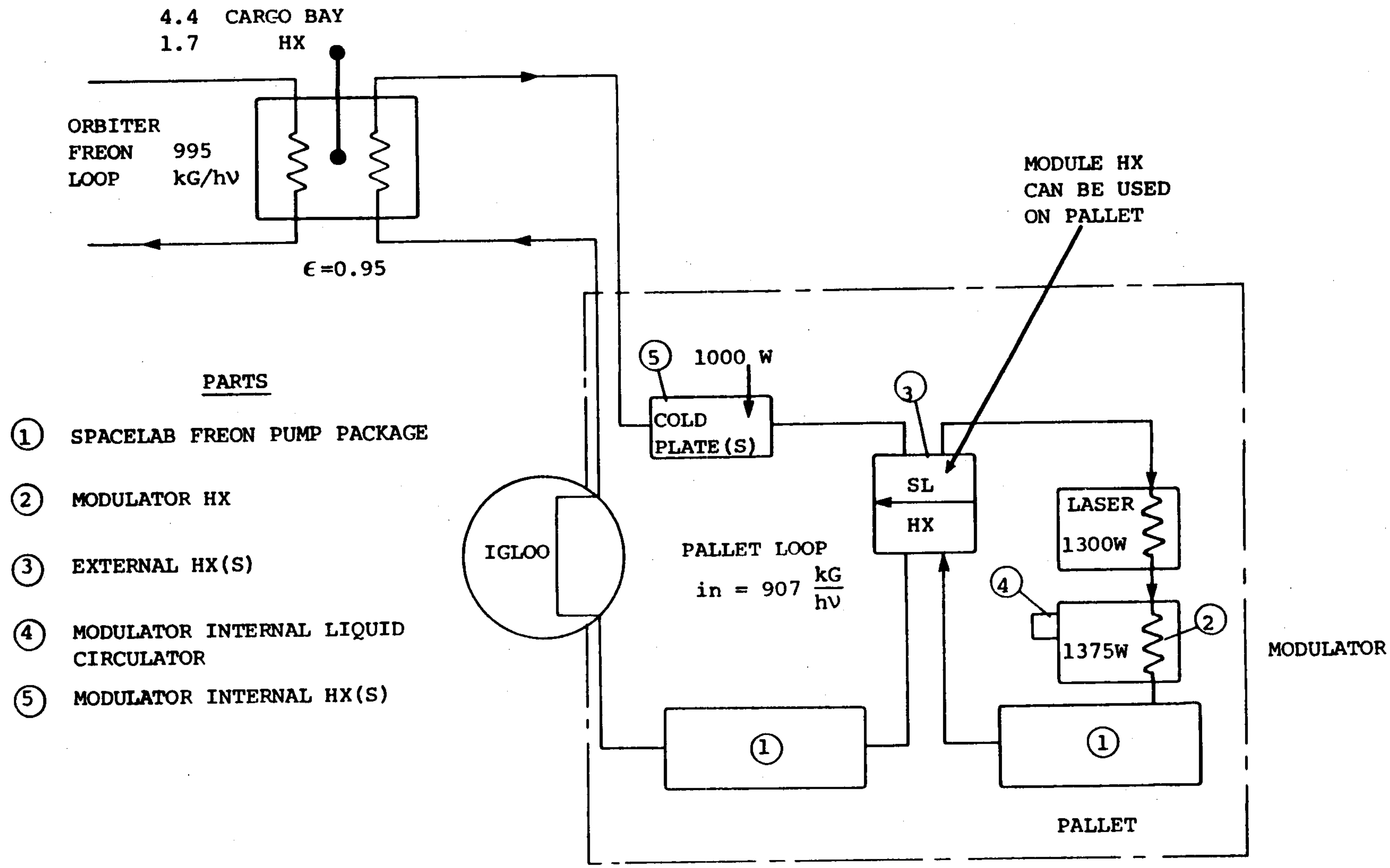

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Figure 3.3-2. Thermal System (PC5-6) Environmental Control HB

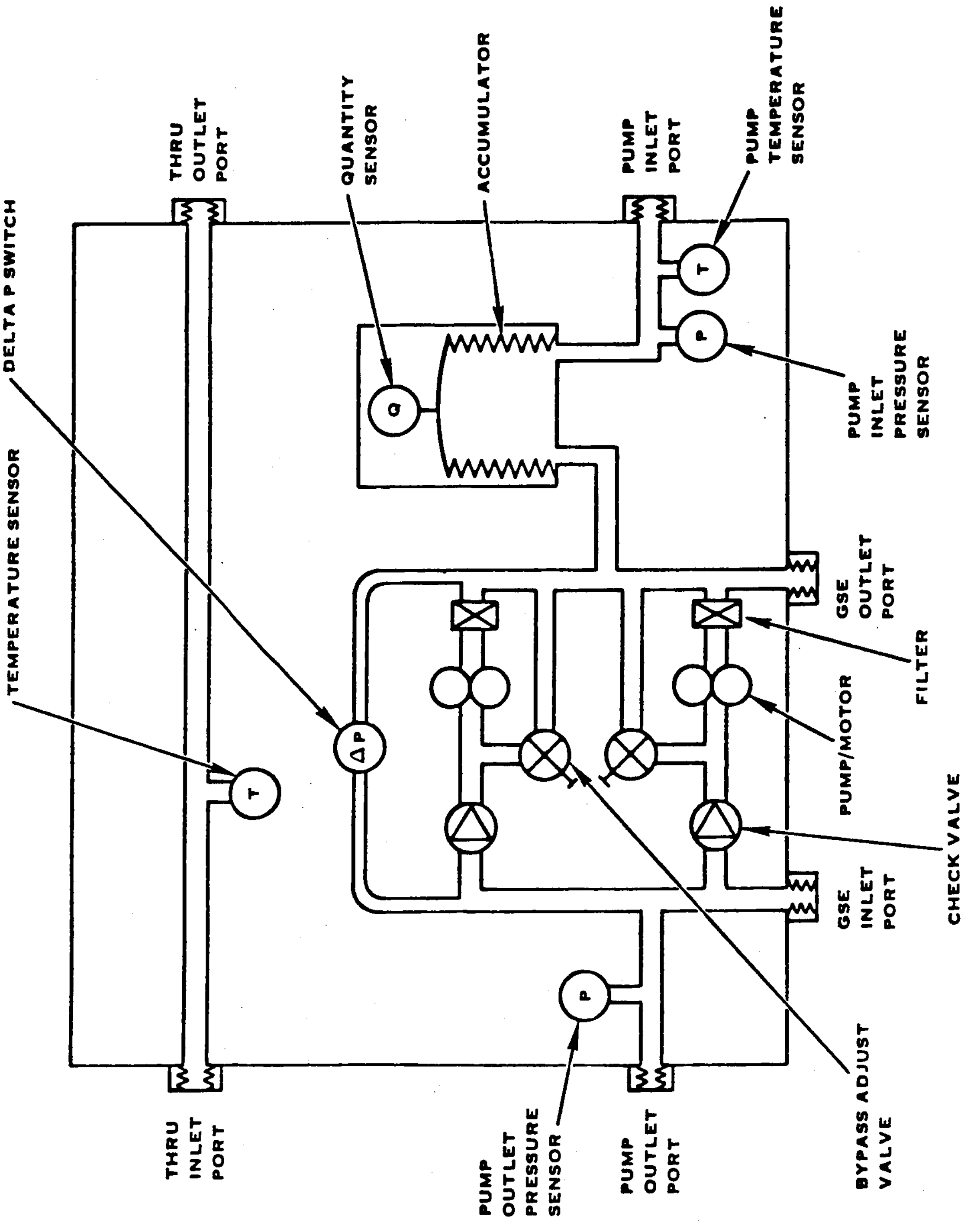
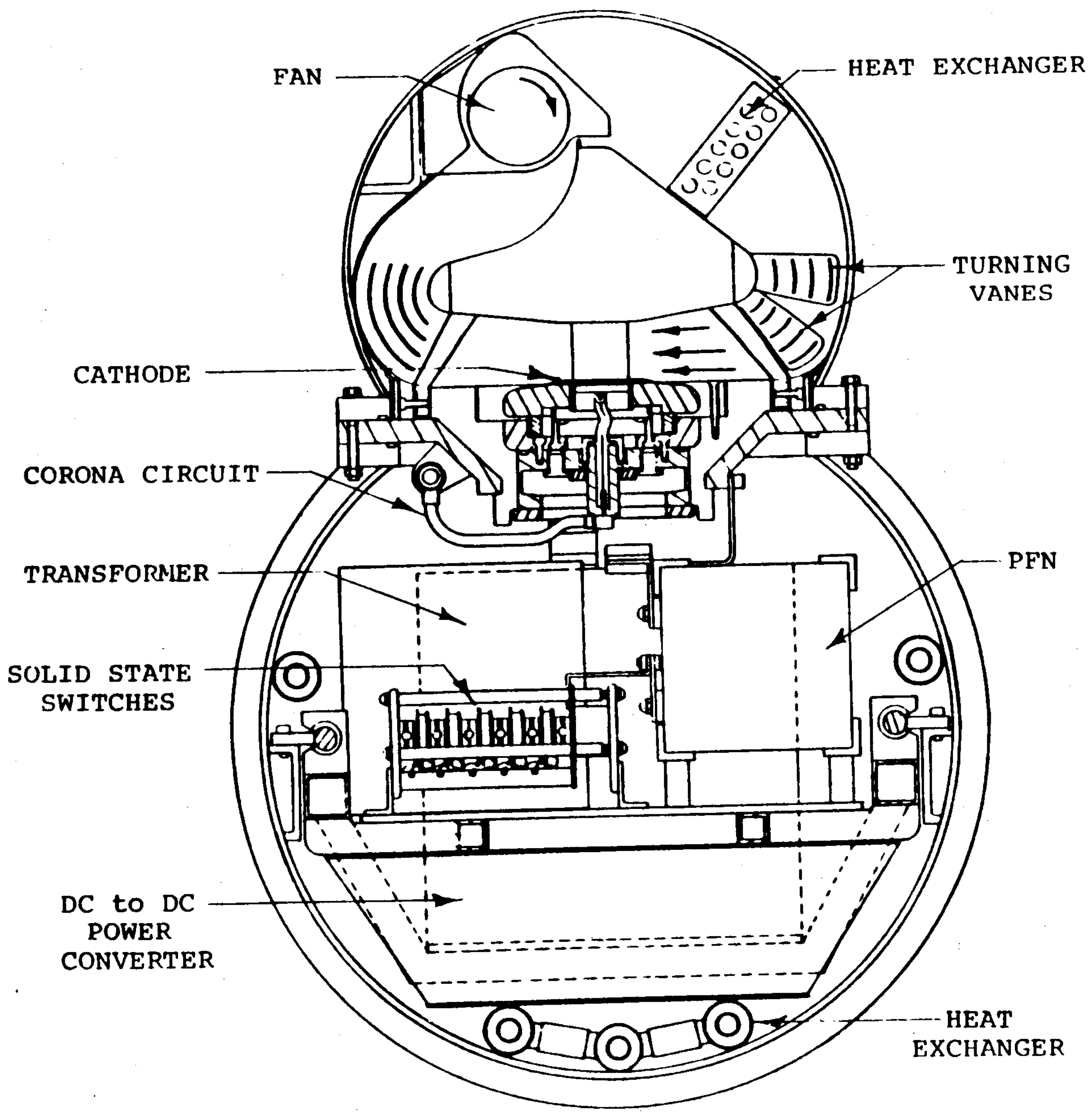


Figure 3.3-3. Spacelab Freon Pump Package Schematic.

equipment. In this latter category are the laser flow loop fan and heat exchanger and the modulator heat exchanger and pumps or fans. From a thermal point of view the laser head flow loop configuration has been engineered to insure that proper forced convection heat transfer is achieved. The heat transfer requirements imposed by the laser performance in the existing WINDVAN device are as stringent as those introduced by the orbiter mission. This is not the case with the modulator cooling. The mechanical and electrical requirements for this subsystem were discussed above and the configuration to meet these has been shown. The thermal requirements for this component, shown in Figure 3.3-4, are likely to be the ones which dominate and which will determine cost and complexity. Figure 3.3-5 shows schematically the four configurations considered for providing cooling to the modulator. The gas version shown in the upper right hand corner is exactly analogous to the laser head flow loop configuration. It involves circulating an electrically insulting coolant gas such as nitrogen or sulfur hexafluoride in a pressurized container. Modulator components would have to be configured in a way which would insure that fresh coolant gas is circulated everywhere throughout the modulator package prevent the buildup contaminants in regions of high electric field stress. The gas/liquid approach is a variation of the gas only version in which the liquid from payload loop is circulated through additional coldplates within the modulator to remove heat from subcomponents generating significant heat. The success of this approach again depends upon providing forced convection throughout the container. The liquid approach uses the payload coolant to address the concentrated heat sources with direct irrigation and the diffuse ones with a parallel flow reaching the rest of the container. The liquid/liquid approach attempts to accomplish the same result but with the addition of an extra pump and heat exchanger the designer is given the choice of coolant/electrical insulator. This may be important for longer missions where liquid degradation may be an issue. For the modest $2x10^7$ shot life requirements of the SCALE mission, coolant life is unlikely to be a problem. Some of the other important considerations in the selection of a modulator cooling approach are listed in Table 3.3-2. The selection of one



LASER

WEIGHT-≃495 lbs
VOLUME-≃4.4 ft^3
(16" dia x 38" lg)

MODULATOR

WEIGHT-≃1000 lbs.
VOLUME-≃8.5 ft^3
(22" dia x 38" lg)

Figure 3.3-4. Laser Head/Modulator.

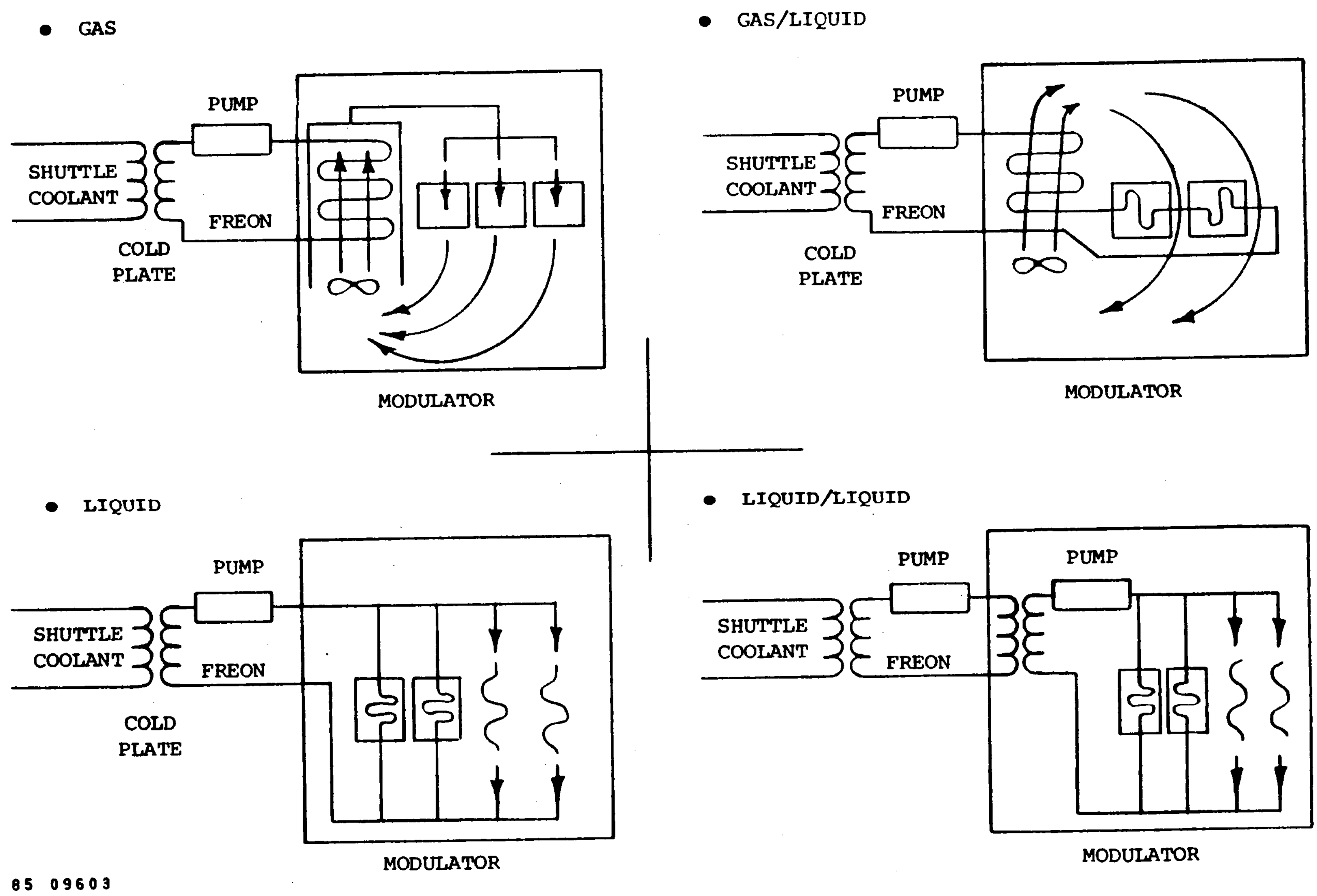


Figure 3.3-5. Modulator Thermal Control.

Table 3.3-2

MODULATOR INSULATOR/COOLING MEDIUM

GAS

Clean

Pressurized Modulator Tank

Gas Flow Through Ducting

Poor Thermal Capacity

Poor Thermal Transfer (Large Hx)

GAS/LIQUID

Clean

Pressurized Modulator Tank

Some Components Directly Cooled

Some Components Gas Cooled

Better Thermal Management of High Power Components

LIQUID

Modulator Components Must be Impregnated With Insulating Fluid (Evacuable)

Good Thermal Capacity

Good Thermal Transfer (Compact Hx)

Incompressible Fluid

Weight May be Greater Than Gas Filled

LIQUID/LIQUID

Same as Liquid

Overall Cooling Efficiency Lower

Modulator Sealed and Self Contained, Needing Only External Cooling Connection

of these approaches will be made after detailed trades during the preliminary design phase.

3.3.3 Criticalities in Thermal System

The first column of Table 3.3-3 lists the thermal system components. The remaining columns of that figure list the environments which are presented to those components during the flight. Components which are sensitive to those environments are flagged in the matrix and as such must be scrutinized during the design and qualification phases to insure that the requirements imposed by the mission on the equipment are met.

3.3.4 Risk Assessment

Table 3.3-4 gives a list of components rated according to the risk assessment scheme presented earlier. The division for risk is by the same catagories delineated above the components with heritage rate as minimal and the experiment specific components indicate the need for risk reduction measures including further design as well as qualification testing. Qualification testing will be required for the modulator the be sure that a forced convection cooling regime is maintained throughout the modulator shell. This will be accomplished by probing the flow field within the modulator as well as measuring the temperatures at strategic locations on internal surfaces.

Summarizing the thermal system design approach: a conservative design approach satisfies mission requirements using a maximum number of space qualified components. Risks are isolated in the modulator where the design has been scoped to the level where it can be stated that this component presents a design problem which is inherently less difficult than the head and flow loop and as such requires a less arduous development effort. Since no design verification tests were required for the thermal aspect of the WINDVAN development program none are anticipated for the modulator packaging.

Table 3.3-3

CRITICALITY OF EQUIPMENT TO DESIGN ENVIRONMENT

SUBSYSTEM: Thermal ITEM	THERMAL VACUUM	THERMAL CYCLE	SINE VIBRATION	RANDOM VIBRATION	ACOUSTIC NOISE	PYROSHOCK	ACCELERATION	HUMIDITY	PRESSURE	LEAKAGE	CHEMICAL CORROSION	SHOCK VIBRATION	FLOW	HIGH VOLTAGE	EMP
Freon Pump Package		o	o	o			o		o	o		o			
Experiment Heat Exchanger		o	o	o	o	o	o		o	o		o	o		
Laser Heat Exchanger		o	o	o	o	o	o		o	o		o	o		
Modulator Heat Exchanger		o	o	o	o	o	o		o	o		o	o		
Modulator Pump		o	o	o			o		o	o		o			
Modulator Flow Dueting		o	o	o	o	o	o						o		

Table 3.3-4

THERMAL COMPONENT RISK ASSESSMENT

SUBSYSTEMS: Thermal

NATURE OF DEVELOPMENT		SUPPORTING ANALYSIS/DATA		FUNCTIONAL CRITICALITY		TOTAL
ITEM	VALUE		VALUE		VALUE	
CATEGORY		CATEGORY		CATEGORY		
ITEM FREON PUMP PACKAGE						
CATEGORY 5	1	4	1	1	3	3
ITEM EXPERIMENT HEAT EXCHANGER						
CATEGORY 5	1	4	1	1	3	3
ITEM LASER HEAT EXCHANGER						
CATEGORY 4	2	4	1	1	3	6
ITEM MODULATOR HEAT EXCHANGER						
CATEGORY 4	2	4	1	1	3	6
ITEM MODULATOR PUMP						
CATEGORY 5	1	4	1	1	3	3
ITEM MODULATOR FLOW DUCTING						
CATEGORY 3	4	3	2	1	3	18

3.4 LASER GAS REGENERATION

The gas lifetime for pulsed, self-sustained discharge CO_2 lasers is limited by the dissociation of CO_2 to form CO and O_2

$$CO_2 \rightarrow CO + 1/2\ O_2$$

Even more important than the loss of the lasing species itself is the gradual buildup of small quantities of O_2 in the gas, which increases the tendency for arc formation. The gas lifetime can be extended by adding small amounts of CO and/or H_2 to the gas mixture in order to force the equilibrium back towards CO_2. However, even with the addition of CO and H_2, the gas mixture must be continually renewed in order to maintain arc free performance. For most applications this is accomplished by slowly flowing new gas into the laser and simply throwing away the old gas. For operation with isotopically selected CO_2 or for space applications where it is not practical or economical to dump the old gas, a catalyst must be employed to reform CO_2.

For purposes of this study three gas make up approaches were considered: Catalytic regeneration, disposal by recompression and storage and finally disposal by jettisoning directly overboard. The last two approaches require a sufficient storage capacity to complete the entire mission. The CO_2 regeneration requirements are shown in Table 3.4-1 for a 3×10^7 shot mission. Regeneration, is the most difficult approach, so it was studied in the greatest detail to provide a conservative baseline. Jettisoning is the simplest approach, and the storage requirements for a 5 day mission are modest. Concerns about contamination of the orbiter bay with spent laser gas must be viewed in context of the 36 pounds of propellant required per 2 minutes yaw maneuver per orbit to maintain the proper ground track for the SCALE mission.

Unless some unforseen requirement surfaces requiring a closed system, overboard dumping with bottle recharge offers a simple and effective choice for gas utilization.

Table 3.4-1

CO_2 GAS REGENERATION REQUIREMENTS

CO_2 Dissociation $\tilde{<}$ 2×10^{-3} Per Pulse

O_2 Production Rate = 1.5 ℓ-Torr/sec at 50 Hz

For Arc Free Performance XO_2 $\tilde{<}$ 5×10^{-3}

Therefore ~0.5% of Main Flow Must be Cleaned Up
For a Discharge Flush Factor of 4

The simplest way to clean up the gas is to flow fresh gas into the laser flow loop and dump the spent gas overboard. Based on the clean up rate of 2ℓ/sec calculated above, 4×10^5 ℓ of gas would be required for 10^7 shots. This requirement can be reduced by adding CO and H_2 to the gas mixture. Our 0.5 J, 50 Hz CO_2 laser CDL-1 required a make-up flow of 10^{-2} ℓ/sec in order to maintain arc free performance. Scaling to Windvan volume and pressure, a flow of 0.35ℓ/sec would be required. This corresponds to a required gas inventory of 7000ℓ for 10^7 shots, which is quite manageable.

3.4.1 Catalytic Regeneration

The options available for catalyst material are shown in Table 3.4-2. Among the catalytic schemes reported for CO_2 regeneration are a hot Pt wire [2] (~1100°C), Pt on Al_2O_3,[3,4] Cu/CuO,[3,5] Hopcalite (60% MnO_2, 40% CuO, and trace quantities of other oxides), [6] and Pt or Pd/SnO_2.[5,7] Hopcalite is a commercially available catalyst and is used in the commercial CO_2 laser produced by Laser Sciences, Inc. It requires the addition of CO to the laser mix for proper operation, and it deteriorates after exposure to H_2O and must be periodically reactivated. Pt or Pd/SnO_2 is a more recent development and is not yet commercially available. However, Engelhard Industries has prepared custom samples for the group at NASA LARC and would presumably be willing to supply them to others.[8] The Pt or Pd/SnO_2 catalysts are approximately a factor of 100 more active than hopcalite and their operation is not degraded by H_2O, but is in fact enhanced.[9] The higher activity for Pt or Pd/SnO_2 means that catalyst can be operated at a lower temperature, which minimizes the amount of power required to heat up the gas flow. In fact, Stark et al. have used this catalyst directly in the main gas flow with the only heat being furnished by the discharge energy addition to the gas.[7]

Table 3.4-2
CATALYSTS FOR CO_2 REGENERATION

	Pt/SnO_2 or Pd/SnO_2	MnO_2/CuO (Hopcalite)
ADVANTAGES	• ~100 times more effective than Hopcalite → lower temperature • Not degraded by water • No bakeout	• Established cataloyst for $CO + 1/2\ O_2 \rightarrow CO_2$ • Demonstrated laser operation • Commercially available
DISADVANTAGES	• Not commerically available • Limited database • Packaging not demonstrated	• Poisoned by water • Effectiveness decays with time • Bakeout required • Lower effectivenss → higher temperature • Small CO addition required

In order to ensure arc free performance, the O_2 concentration must be kept $\lesssim 0.5$ percent.[7] The amount of CO_2 dissociation per pulse can be estimated from the measurements of Pace and Lacombe on a corona preionized CO_2 laser with approximately the same energy loading as for our Windvan Laser.[10] They found that there was essentially no reformation of CO_2 up to about 4000 pulses, at which time approximately 8 percent of the CO_2 had been dissociated. This number must be multiplied by the ratio of their total loop volume to the discharge volume ($\sim$ 5.6ℓ/30 cm³ = 187) and divided by the number of pulses to give a CO_2 dissociation rate of 0.36% per pulse in the discharge volume. The O_2 production rate is half of the CO_2 dissociation rate or 0.18% per pulse. For Windvan operation at 50 Hz and with 30 Torr CO_2, the estimated O_2 production rate is $\sim 1.8 \times 10^{-3} \times 30$ Torr x 50 Hz x 1ℓ/discharge volume = 2.7 Torrℓ/sec. To maintain the O_2 concentration at $5 \times 10^{-3} \times 300$ Torr = 1.5 Torr, a gas flow of approximately 2ℓ/sec must be cleaned of O_2. The flush factor for the main flow in Windvan is $\sim$4, so that the volume flow rate is 50 Hz x 1ℓ x 4 = 200ℓ/sec. Thus approximately 1% of the main gas flow must have the O_2 removed in order to keep the O_2 concentration at a low enough level to permit arc free operation.

The catalytic oxidation of CO to reform CO_2 is shown schematically in Figure 3.4-1. A portion of the main gas flow is directed over the catalyst bed and then routed back through a heat exchanger to cool the gas. Depending on the amount of gas which must be cleaned, the catalyst can be located outside the main flow loop with its own fan or actually be inserted in the main gas flow loop without the need for a separate fan.[7] Locating the catalyst in the main flow loop minimizes the amount of ancillary equipment required. The catalyst would be heated by the hot gas from the discharge. If the catalyst can be coated onto some support plate and still maintain a large surface area without spreading dust all over the laser, then an array of plates can be placed in the main flow loop. The ratio of the length of the plates in the flow direction to the spacing perpendicular to the flow direction would be chosen to assure good contact of the gas with the catalyst, in a way similar to the design of heat

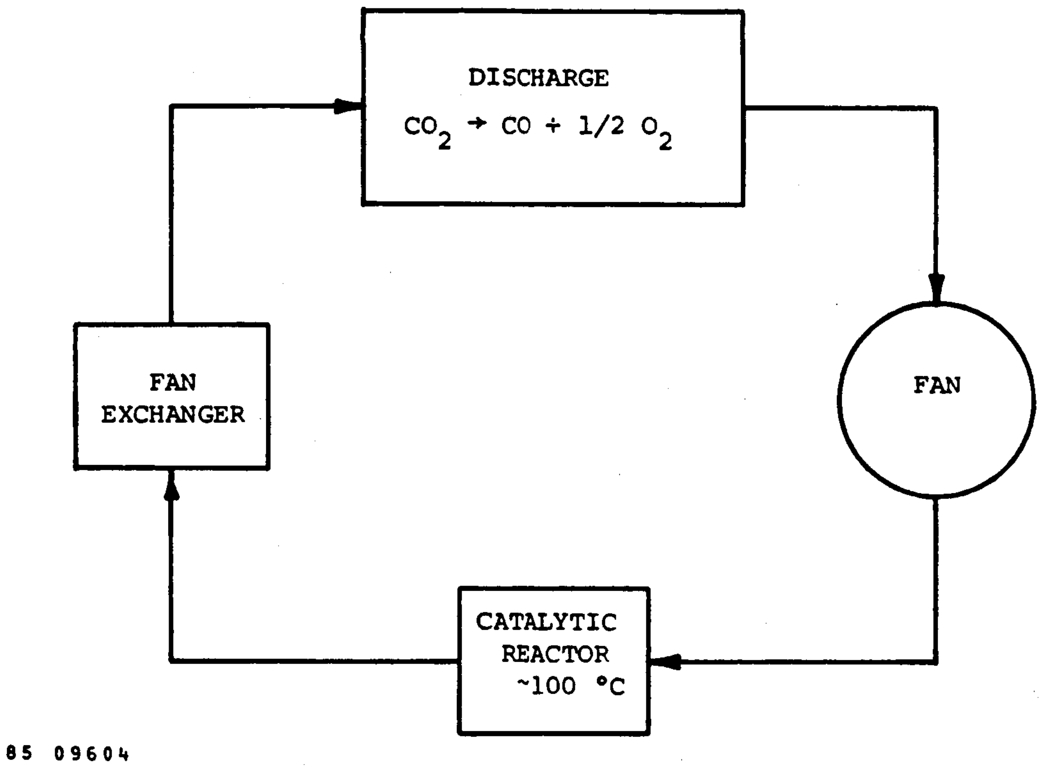


Figure 3.4-1. Catalytic Gas Regeneration System.

exchangers. The extra flow impedance would increase the fan power by about the same amount as the heat exchanger (~10% of the present flow power). Although operation of the catalyst in the main flow loop has been demonstrated,[7] no discussion was presented of how well the catalyst adhered to the mounting plates or how much dust was spread throughout the flow loop.

By placing the catalyst in an external loop, dust can be controlled with a particle filter at the expense of increased pressure drop. In addition, the catalyst temperature can be increased so that the required amount can be reduced. However, an extra fan is required along with its fan power and the extra heat to raise the gas temperature to the catalyst temperature. Because of the unresolved issue of encapsulating the catalyst without reducing its surface area, we have selected the external catalyst loop as our baseline approach. The layout is shown in Figure 3.4-2. A portion of the laser gas flow is extracted from the laser flow loop downstream of the discharge. The external fan circulates the gas through a counterflow heat exchanger and a heater to raise its temperature to the temperature of the catalyst bed (~100°C). The gas then passes through the catalyst bed to reoxidize CO and O_2, a filter to remove any dust, and then through the counterflow heat exchanger to be cooled before re-entering the main flow loop downstream of the transverse fan. A space qualified fan manufactured by Hamilton Standard (Model #SV755524) has been identified for this application. It can provide a volume flow rate of 100 at a lift of 3 in H_2O and requires an electrical input power of 180 W.

The weight of catalyst required can be estimated from the data of Stark and Harris[7] and from the data of Miller, et al.[11] Stark and Harris have measured a volumetric O_2 recombination rate of ~3×10^{-4} ℓ sec^{-1} g^{-1} at 40°C with an activation energy of 41.4 kJ/mole for Pt/SnO_2. Using this number together with the estimated O_2 production rate of 2.7 Torr ℓ/sec for Windvan gives a catalyst weight of 6 kG to keep the O_2 partial pressure below 1.5 Torr. This amount of catalyst can be reduced to ~0.5 kG by increasing the catalyst temperature to 100°C.

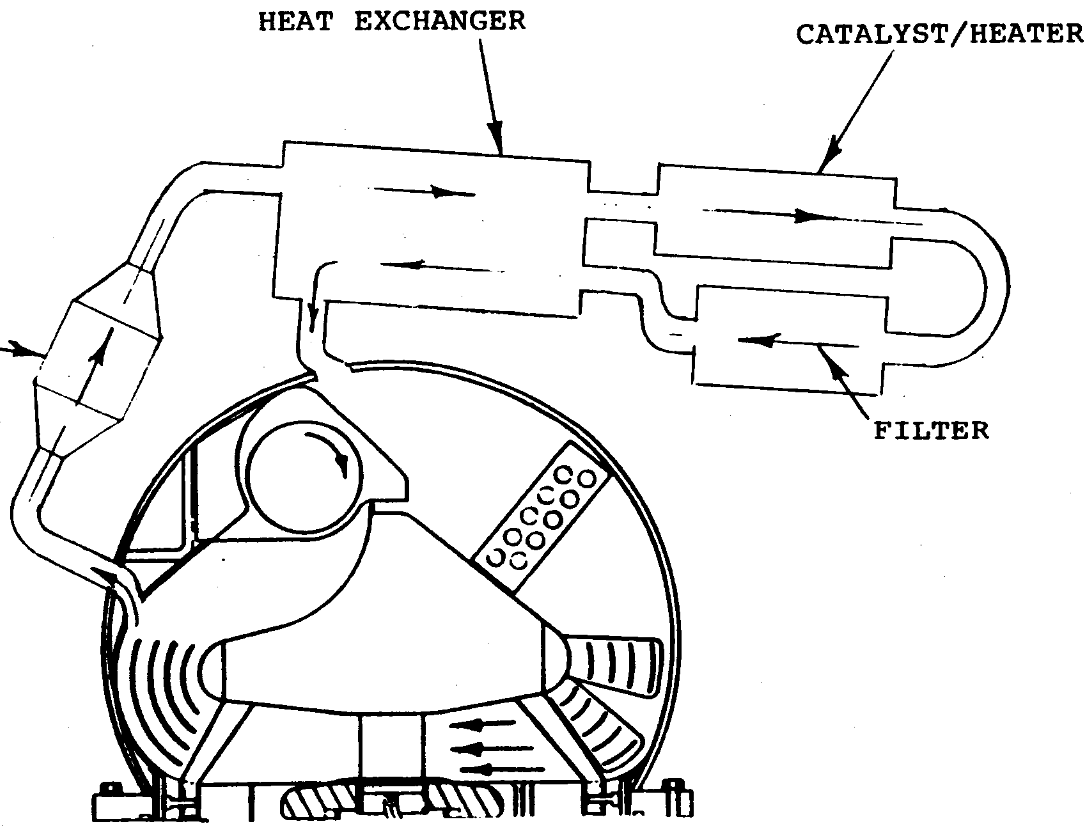


Figure 3.4-2. Gas Processor Configuration.

The results of Miller, et al.[11] give a different method for estimating the required weight of catalyst. They relate the weight of catalyst w to the contact time τ, the volume flow rate F, and the catalyst specific void volume V'_o according to

$$W = \frac{F\ \tau}{V'_o}$$

They have determined the catalyst specific void volume for Pt/SnO_2 to be V_o = 0.374 cm³/g and the required contact time for complete conversion of CO and O_2 to CO_2 to be ~1.5 sec at T = 100°C. For our required clean up flow rate of 1000 standard cm³/sec,

$$W = \frac{1000\ (1.5)}{0} .374 = 4\ \text{kG}.$$

This is considerably larger than the amount estimated from the Stark and Harris results scaled to the same temperature. These results are summarized in Table 3.4-3.

For operation with isotopically selected CO_2, the results of Hess, et al.[4] indicate isotopic scrambling from the SnO_2 catalyst component. Preliminary results indicate that this scrambling can be controlled by first reducing the catalyst surface with H_2 and then reoxidizing with $^{18}O_2$. However, the long term effectiveness of this treatment has not been demonstrated yet. Even if the surface treatment is not effective, the isotopic scrambling can be controlled by completely forming the SnO_2 from $^{18}O_2$, although the cost would be high for the estimated 4 kG of catalyst.

The work of Stark and Harris and Hess and co-workers indicate that Pt or Pd/SnO_2 is a very promising catalyst for closed cycle CO_2 lasers. The main remaining issues for our application are demonstration of long term operation for >10⁷ shots, demonstration of some method of encapsulating the catalyst without reducing its surface area, and control of the isotopic scrambling for use with rare isotope mixtures. Work on the development of

Table 3.4-3

AMOUNT OF CATALYST REQUIRED

AMOUNT OF CATALYST	
Scaling from LaRC results (T ~ 100°C)	220 g
Scaling from RSRE laser results (T ~ 40°C)	580 g
Scaling from RSRE reaction results (T ~ 40°C)	2250 g
Heater Power for 100°C Operation	10 W
Circulator Power	180 W

Pt/SnO_2 catalysts is continuing at NASA LaRC. In addition, the effectiveness of the catalyst could be tested at STI using our 50 Hz CDL-1 CO_2 laser to demonstrate operation for $>10^7$ shots while monitoring the O_2 concentration in the laser gas. This could be done either with an external catalyst loop or with the catalyst in the main laser flow loop and could also be used to investigate rare isotope mixtures. The CDL-1 laser is very similar to Windvan in that it is a corona preionized discharge laser with a 50 Hz repetition rate and transverse fan/compact flow loop configuration. However, the CDL-1 laser is considerably smaller and would minimize the amount of gas and catalyst required, as well as the time and cost for modifications. One of these laser systems is currently available at STI. The design database for the Pd or Pt/SnO_2 catalyst is given in Table 3.4-4.

3.5 OPTICAL/STRUCTURAL

3.5.1 WINDVAN Optical Configuration

The small optics which process the cw laser beams are straightforward. All of these optics are ZnSe components with appropriate coatings. The periscope which brings the IO beam down to table level also causes a polarization rotation, so that the two beams are in opposite polarizations as they cross the table. This fact is used to advantage in tuning the various beam intensities at the detectors. A beamsplitter picks off the IO sample for the lock detector. The sample is focused on the detector through a rotatable wire grid polarizer that is used to optimize the intensity.

A pair of beamsplitters picks off the samples of both beams needed by the IO/LO beat detector. These two beams are colinear after the second beamsplitter but have crossed polarizations. The combined beam is focused onto the beat detector through a pair of wire-grid polarizers. The first polarizer changes the ratio of the two beams presented to the detector, while the second (or its angle relative to the first) changes the total signal level.

Table 3.4-4

DATABASE FOR Pd or Pt/SnO_2 CATALYST

Start, et al. (RSRE) Demonstrated Control of XO_2 ~< 0.5% for 1.5 x 10^6 Shots at 20 Hz

- Catalyst located in main flow loop
- Temperature ~40°C

Hess, et al. LaRC) Demonstrated Control of XO_2 ~< 0.5% for 1.5 x 10^5 at 10 Hz

- Catalyst located in external flow loop
- Laser power ~90% initial power at 100°C

LaRC Preliminary Tests with $C^{18}O_2$ Indicate That Isotopic Scrambling can be Eliminated by Pretreatment with $^{18}O_2$

- Reduce surface with H_2 to remove ^{16}O and re-oxidize with $^{18}O_2$

Table 3.4-5

CRITICALITY OF EQUIPMENT TO DESIGN ENVIRONMENT

SUBSYSTEM: Gas Regeneration

ITEM	THERMAL VACUUM	THERMAL CYCLE	SINE VIBRATION	RANDOM VIBRATION	ACOUSTIC NOISE	PYROSHOCK	ACCELERATION	HUMIDITY	PRESSURE	LEAKAGE	CHEMICAL CORROSION	SHOCK VIBRATION	FLOW	HIGH VOLTAGE	EMP
Blower						o			o	o			o		
Regenerative Heat Exchanger		o	o	o	o	o	o		o	o		o	o		
Catalyst Container									o	o					
Catalyst Charge		o	o	o	o	o	o		o			o	o		
Catalyst Heater		o	o				o					o			
Filter		o	o	o	o	o	o		o			o	o		

Table 3.4-6
GAS REGENERATION COMPONENT RISK ASSESSMENT

SUBSYSTEM: Gas Regeneration

NATURE OF DEVELOPMENT		SUPPORTING ANALYSIS/DATA		FUNCTIONAL CRITICALITY		TOTAL
ITEM	VALUE		VALUE		VALUE	
CATEGORY		CATEGORY		CATEGORY		
ITEM BLOWER						
CATEGORY 5	1	4	1	1	3	3
ITEM REGENERATIVE HEAT EXCHANGER						
CATEGORY 4	2	4	1	2	2	4
ITEM CATALYST CONTAINER						
CATEGORY 4	2	4	1	1	3	6
ITEM CATALYST CHARGE						
CATEGORY 4	2	4	1	1	3	6
ITEM CATALYST HEATER						
CATEGORY 4	2	4	1	2	2	4
ITEM FILTER						
CATEGORY 4	2	4	1	2	2	4

Table 3.4-7

CATALYST DESIGN VERIFICATION TESTS

ISSUES

- Scaling to 50 Hz Operation

  Required catalyst surface area

- Isotopic Scrambling

  Is surface replacement with ^{18}O sufficient

DEMONSTRATION OF 10^7 SHOT OPERATION AT 50 Hz

- Use Markem CO_2 Laser with Catalyst Loop
- Monitor O_2 Concentration and Laser Power
- Repeat with Isotopically Selected $C^{18}O_2$

A number of small copper steering mirrors are used to transport the beams across the small NRC breadboard. The LO beam leaves the table, while the IO beam is taken to the input coupling hole of the PO through a beamsplitter, which samples the backscattered wave from the PO oscillator. This last beamsplitter generates the sample needed by the PO lock detector.

The heart of the system is the power oscillator resonator. This is a positive branch unstable resonator, with the large mirror (primary) replaced by a Littrow diffraction grating to provide rotational line selection. Outcoupling is from a diagonal scraper mirror located just inside of the secondary. The magnification of the resonator is 1.7. Wave optics calculations show that the actual outcoupling for the resonator is about 40 percent.

This resonator is not confocal, since to build a confocal resonator would have required a large, expensive, and perhaps even unobtainable curved diffraction grating. The use of a flat grating results in a mode that is slightly diverging at the output. The divergence angle is ≈ 2.4 mrad. Note that this divergence does not represent a loss of beam quality. There is no loss of beam focusability, but there is a focal shift due to the divergence.

The injection laser is introduced thorugh a small hole drilled in the secondary mirror. The size of this hole is selected as a compromise between incoupling efficiency and the effect of the hole on the unstable resonator mode. The critical parameter is the radius of the resonator Fresnel core, which is given by a = sqrt($\lambda \ell$). If the injection hole radius is small compared with a, then the mode is little affected by the presence of the hole. On the other hand, the effective incoupling efficiency decreases roughly as the area of the hole. For the PO resonator, a = 6 mm, while we have chosen an incoupling hole radius of 1.5 mm.

The proper PO resonance condition is identified by sensing the standing wave power in the resonator due to the IO between pulses. When the PO mode has the same frequency as the injection signal, then the standing wave power inside the Fresnel core builds to a maximum. This process is exactly analogous to a conventional Fabry-Perot except that part of the feedback process that leads to standing wave buildup is due to diffraction rather than simple reflection. Nonetheless, the same phenomenology applies, and the internal standing wave power is at a maximum when the input signal and cavity are resonant. The existence of this resonance is detected by looking at the power propagating back through the injection port, which is simply a sample of the on-axis standing wave power.

The servo system, which must locate the maximum, or zero derivative point, requires a dither. Rather than dithering the cavity length, we exploit the fact that the injection signal is already frequency modulated due to the IO dither. The comparison of input frequency and cavity length is made by dithering the frequency rather than the length.

Finally, after the pulsed beam leaves the PO resonator, it is demagnified by an inverted Cassegrian-type telescope to a nominal diameter of 18 mm before leaving the laser system. The telescope exploits the annular nature of the beam from the PO to perform this function without any shadowing loss due to the secondary mirror. The mirror spacing is increased above the confocal value to compensate for the diverging output mode from the PO resonator.

The optical system for the SCALE transmitter is identical in size and spatial configuration with the WINDVAN configuration. The WINDVAN design required a degree of hardening over what might be required of a laboratory device due to the extremes of environment to which it is exposed when mounted in a trailer. Rough terrain and temperature extremes, comparable

in range with the SCALE mission, required careful attention during the design phase. The primary concern in achieving a successful upgrade of WINDVAN to the SCALE mission is the need to maintain the physical alignment of the system during launch and on station maneuvers. Adjustments to the WINDVAN system by the operators in the field are required to keep the optical system in proper alignment. These adjustments are simple and are accomplished manually by manipulating mirror mount micrometer actuators in conjunction with targets inserted into the beam path. Performing such procedures remotely becomes an exceedingly difficult task requiring a large number of actuators and detectors in a control system of formidible complexity. Since remote operation is the only mode under consideration for the SCALE mission, a great deal of attention has been given to this problem during this study. The objective is to characterize the problem quantitatively by examining the thermal and mechanical design environment on a space hardened configuration composed of the minimum number of subunits which could be aligned with respect to one another and to assign values to the allowable errors for each of the components in the optical system.

3.5.2 Optical System

The schematic layout of the transmitter system was shown previously in Figure 2-1. The physical layout is shown in Figure 3.5-1. The plan view shows the size and location of each of the elements of the system. A structural concept which addresses the design issues presented above is shown in Figure 3.5-2. Separately mounting the laser from the optical bench, with the latter containing the transmitter cavity optics and the rest of the components, serves the dual purpose of isolating the relatively massive laser head from the rest of the optics during the potentially destructive launch phase and preventing vibrations originating in the laser from affecting the optics during transmitter operation. Statically determinate truss systems provide a strain-free mounting structure for the bench and the laser/modulator. An additional feature shown in the figure is an acoustic barrier that surrounds the optical bench to attenuate the

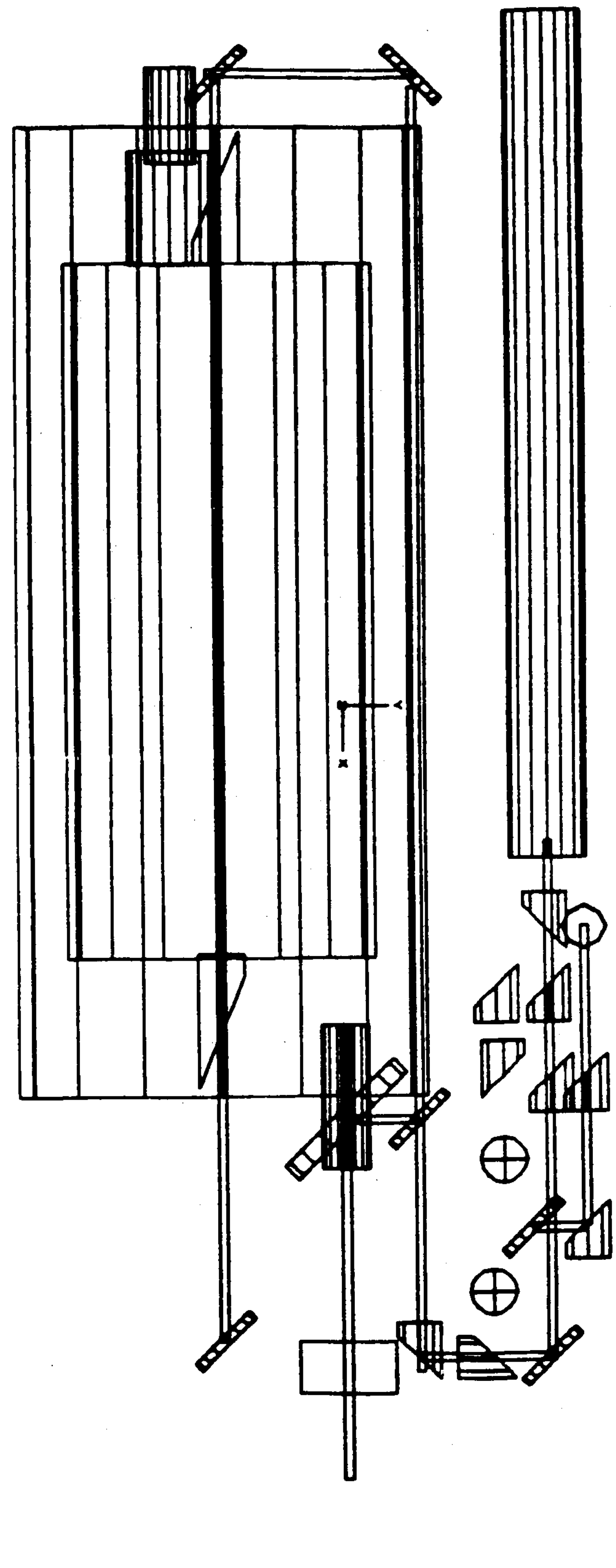


Figure 3.5-1. WINDVAN Optical Layout

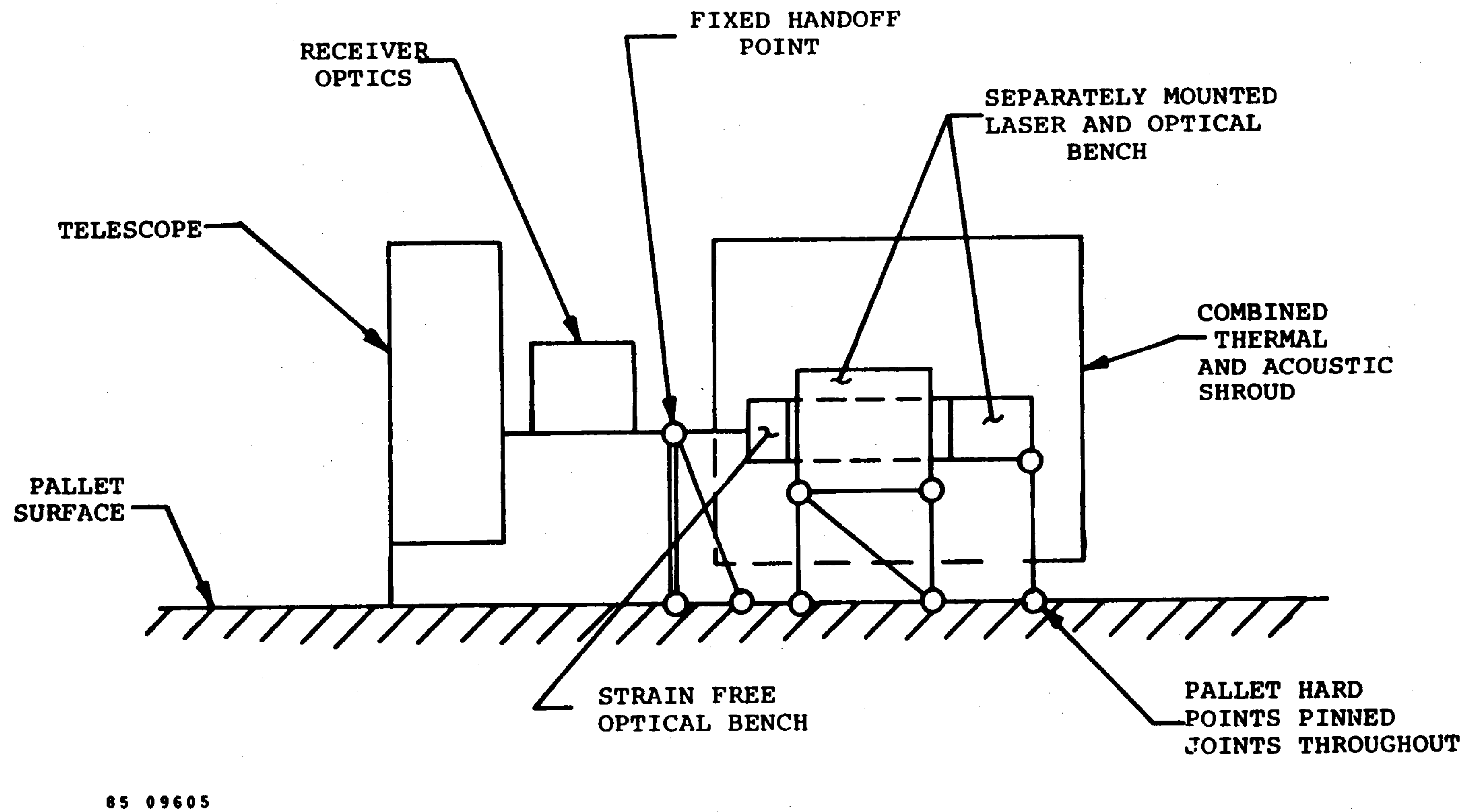


Figure 3.5-2. Structural Concept

large amplitude pressure waves present in the cargo bay during the launch. The structural relationship between the transmitter and the rest of the major SCALE components also is shown. The advantage of interconnecting these components at a single fixed hard point is that the thermal expansion of the components can take place in a controlled way.

The physical manifestation of this approach is shown in Figure 3.5-3. The laser, the optical bench, and the acoustic shell are shown rigidly attached to the ESA pallet. The intended function can be accomplished equally well by reinforcing the shell structure until it is comparable in stiffness to the pallet structure and then mounting the laser and bench directly to the shell. Details of the expected performance of each of these components are given below.

The laser mounting scheme shown in Figure 3.5-4 illustrates the load path from the laser/modulator to the ESA pallet hardpoints via a system of ball and socket mounted rigid rods, with the shells of the laser and modulator acting as load carrying structure. The truss system fixes one end of the laser on the pallet, with the other end unrestrained in the axial direction. Figure 3.5-5 shows a similar arrangement for the optical bench. The table is made of low coefficient of thermal expansion material as is the space frame holding the cavity optics. Three options for the optical table design include: (1) a custom-fit unit with carbon fiber L-brackets molded into the table surface; (2) a flat carbon fiber table with simple brackets; and (3) a semi-kinematic space frame or a regular optical table with fully kinematically mounted spaceframe for resonator optics, i.e., the WINDVAN approach.

The details of the acoustic protection system are shown in Figure 3.5-6. An external thermal blanket provides thermal insulation and some degree of sound attenuation. An aluminum skin on the outside of a monocoque shell structure protects against the cargo bay noise and an open cell lead foam, such as that used to isolate passengers from the engine noise on commercial aircraft, prevents the build-up of disturbances within the shell.

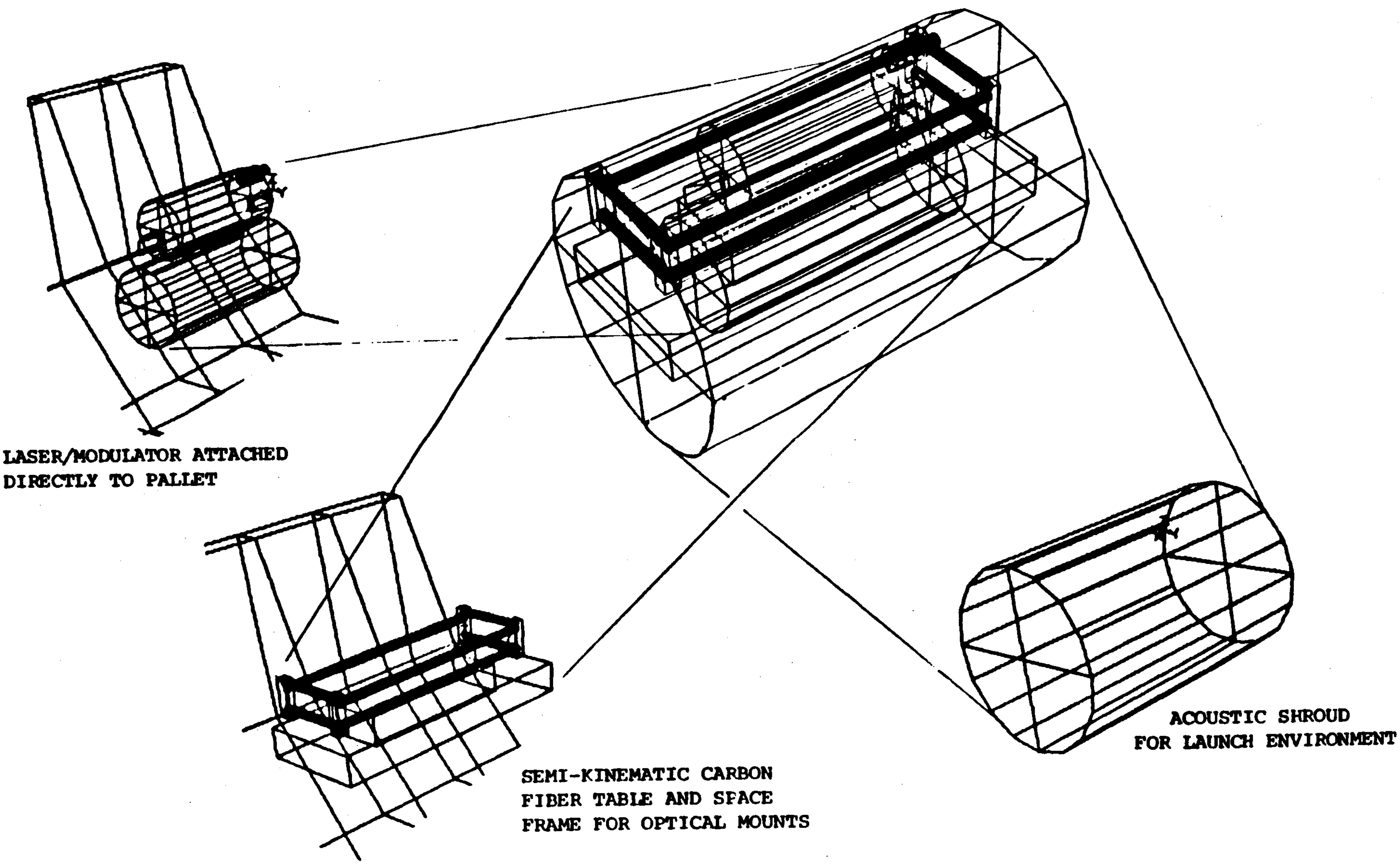
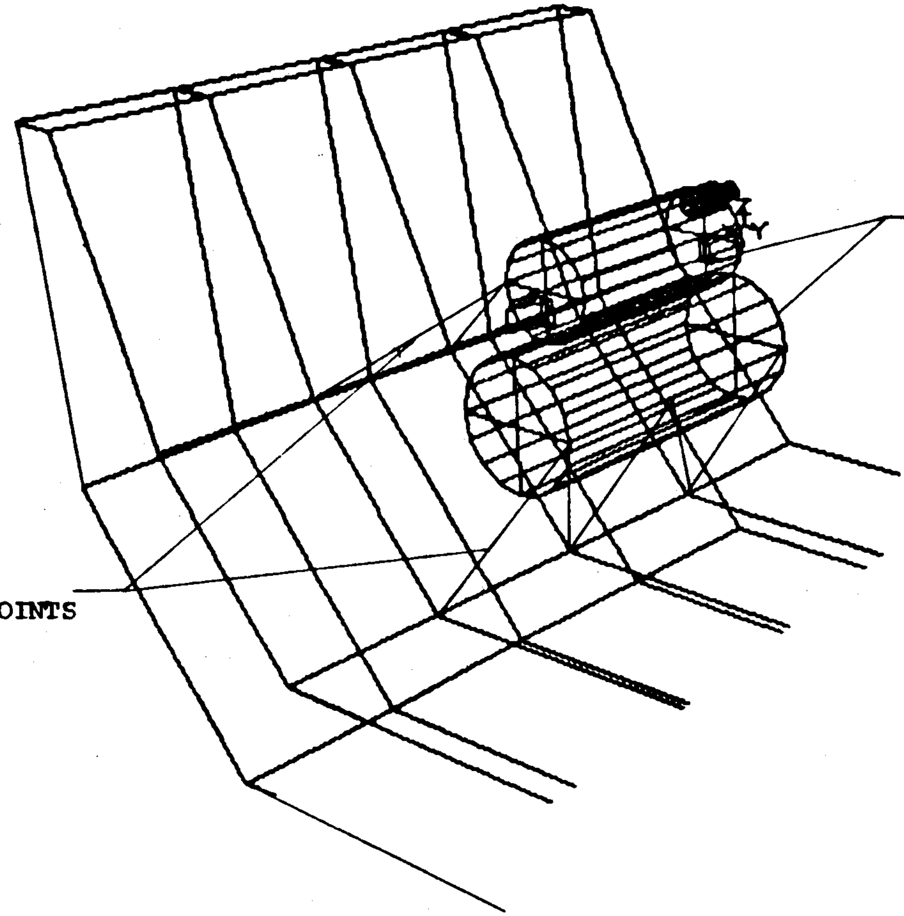
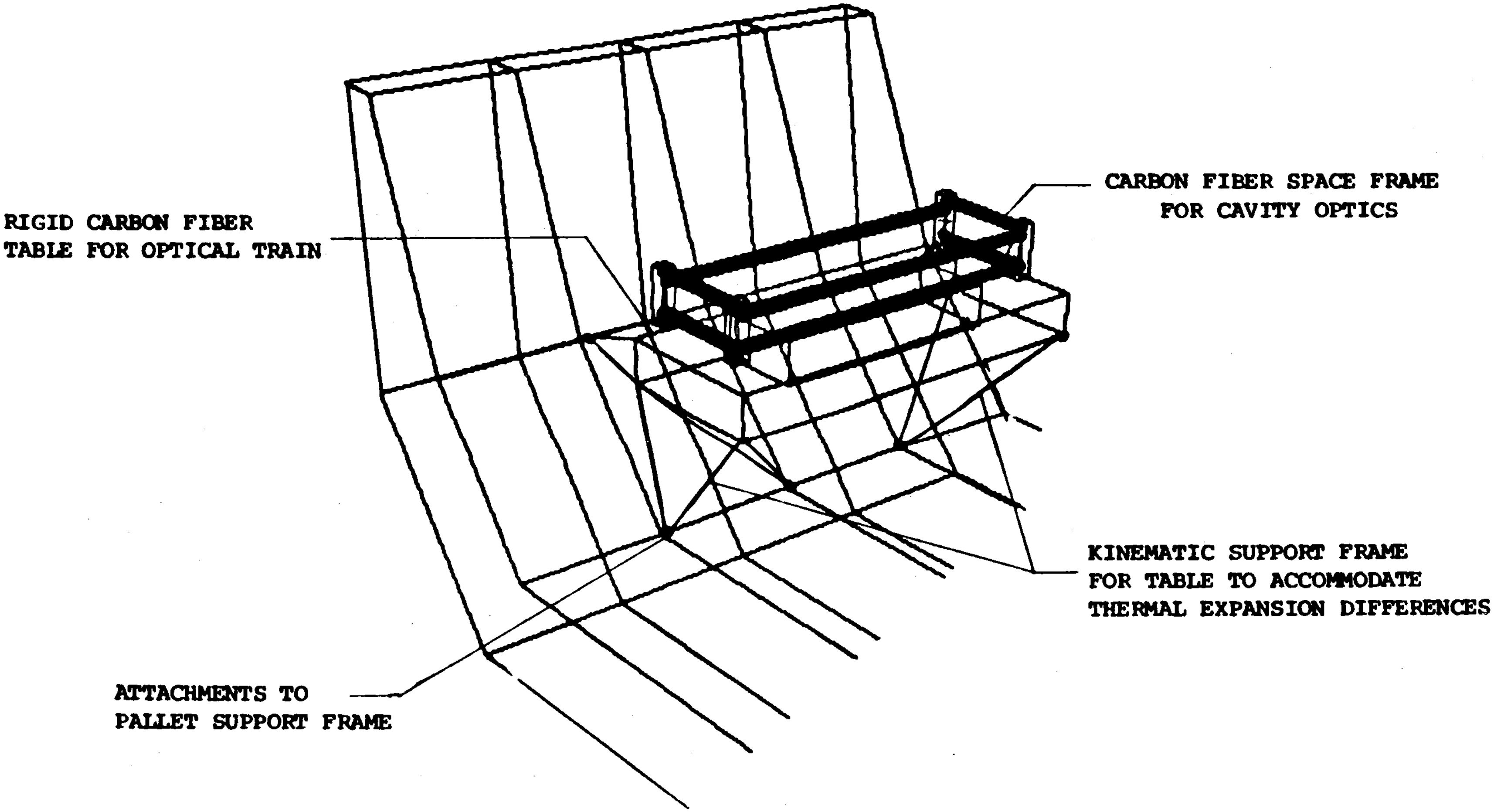


Figure 3.5-3. Structural Configuration



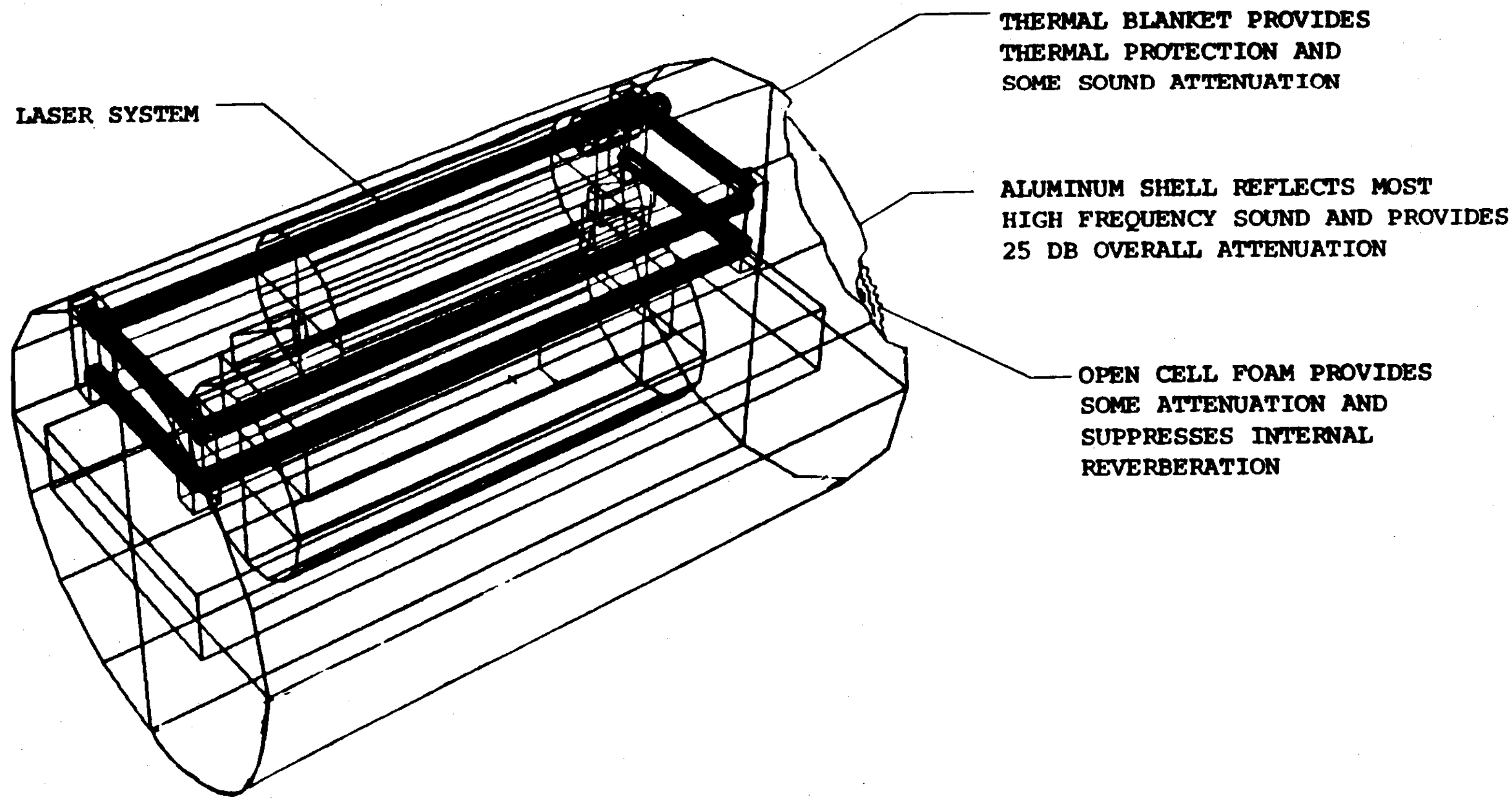
85 09599

Figure 3.5-4. Laser/Modulator Mounting



05 09598

Figure 3.5-5. Optical Table and Space Frame



85 09601

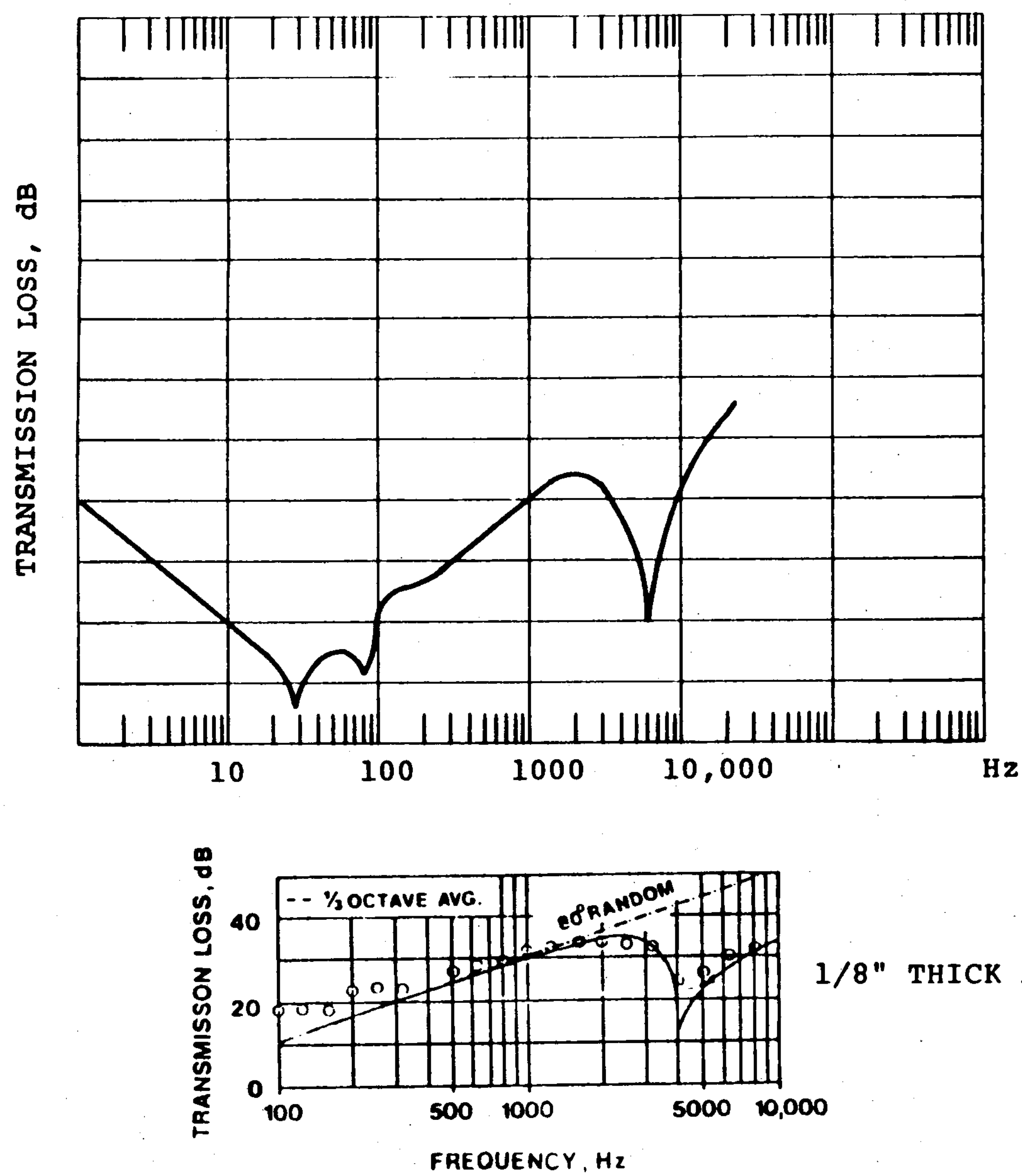
Figure 3.5-6. Acoustic Protection System

The performance of a simple acoustic shield is shown in Figure 3.5-7. In the region below 20 Hz, the sound wave buffets the structure, with the effects being felt increasingly as the first resonance, the out-of-round flexing of the cylinder, is approached. In the region above the first resonance, the inertia of the wall attenuates with a f^{-2} dependence. At very high frequencies, transverse modes within the walls decrease the shell's performance.

Figure 3.5-8 shows the magnitude of the acoustic problem in the shuttle bay during launch. The upper curve in that figure gives the spectrum of the acoustic noise in the shuttle bay. The peak intensity occurs at around 400 Hz and has a magnitude of 145 dB. This level can be expected to misalign components. With the addition of the simplest shroud, the 1/8 inch shell, the peak amplitudes (see lower curve) drop by 20 dB to a level which the mounts can be expected to tolerate.

To provide an additional degree of confidence that a largely passive alignment approach would be attainable, a test was performed on a commercially available flexure mount. Figure 3.5-9 shows the test setup and the results. A laser ranger and reflecting optic sensitive to 0.1 arc were used to measure the relaxation of the mount, which was subjected to intense vibration at its set-screw adjustments from an engraving tool. The results show a decrease in drift with vibration time, suggesting that this method, if used to stabilize the optical alignment before launch, can be expected to hold the alignment within the error budget through launch.

Defining an alignment strategy that would insure the success of the mission while minimizing the number of active elements was also addressed as part of the optics task. The first step is to divide the lidar system into physically related subunits. This is illustrated in Figure 3.5-10. The next goal is to provide adequate passive stability within subunits; active alignment is then provided between subunits, as needed. The



GENERIC SOLID SHELL

1/8" THICK Al SHELL

Figure 3.5-7. Acoustic Performance of Simple Shield

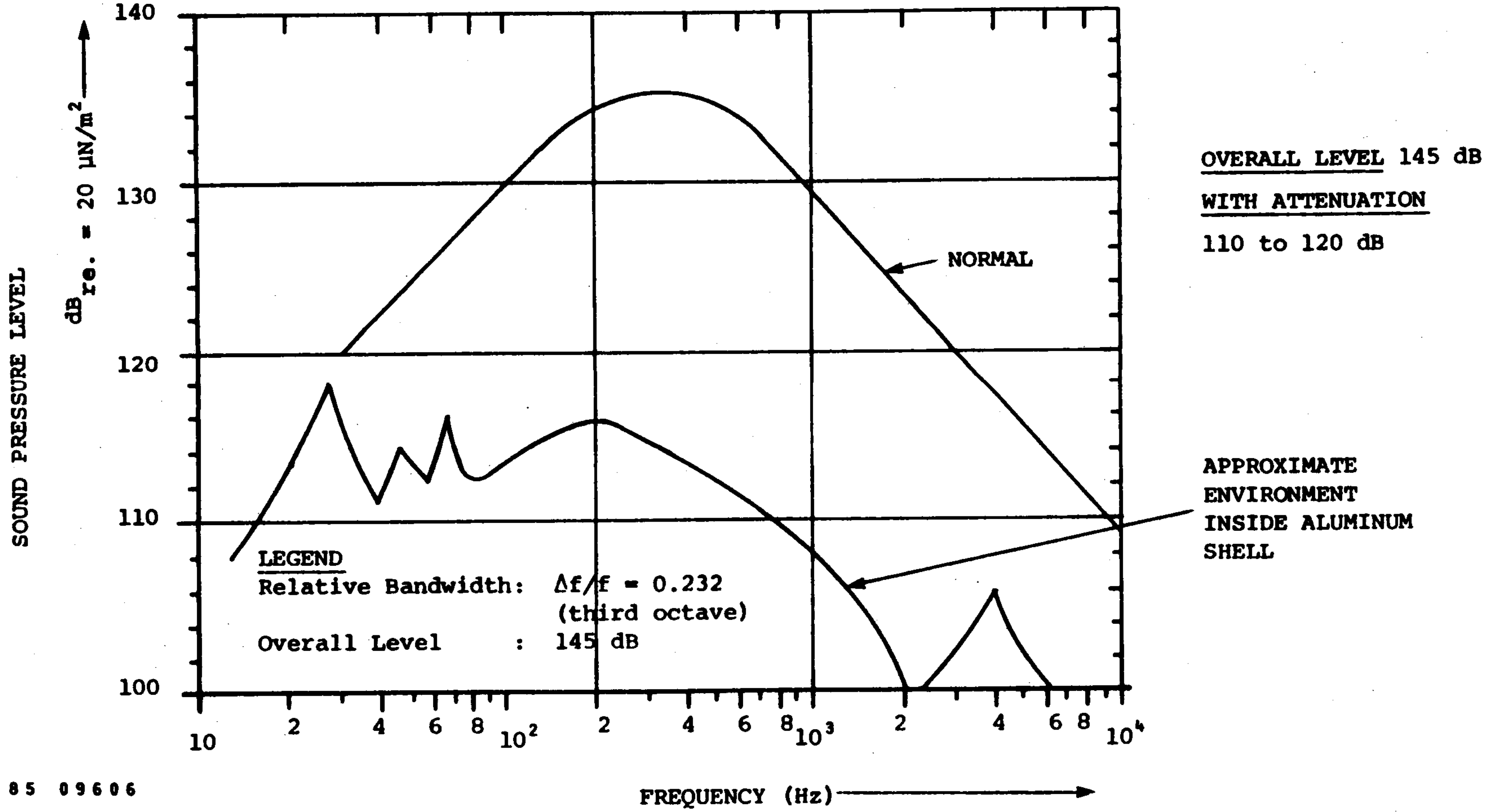
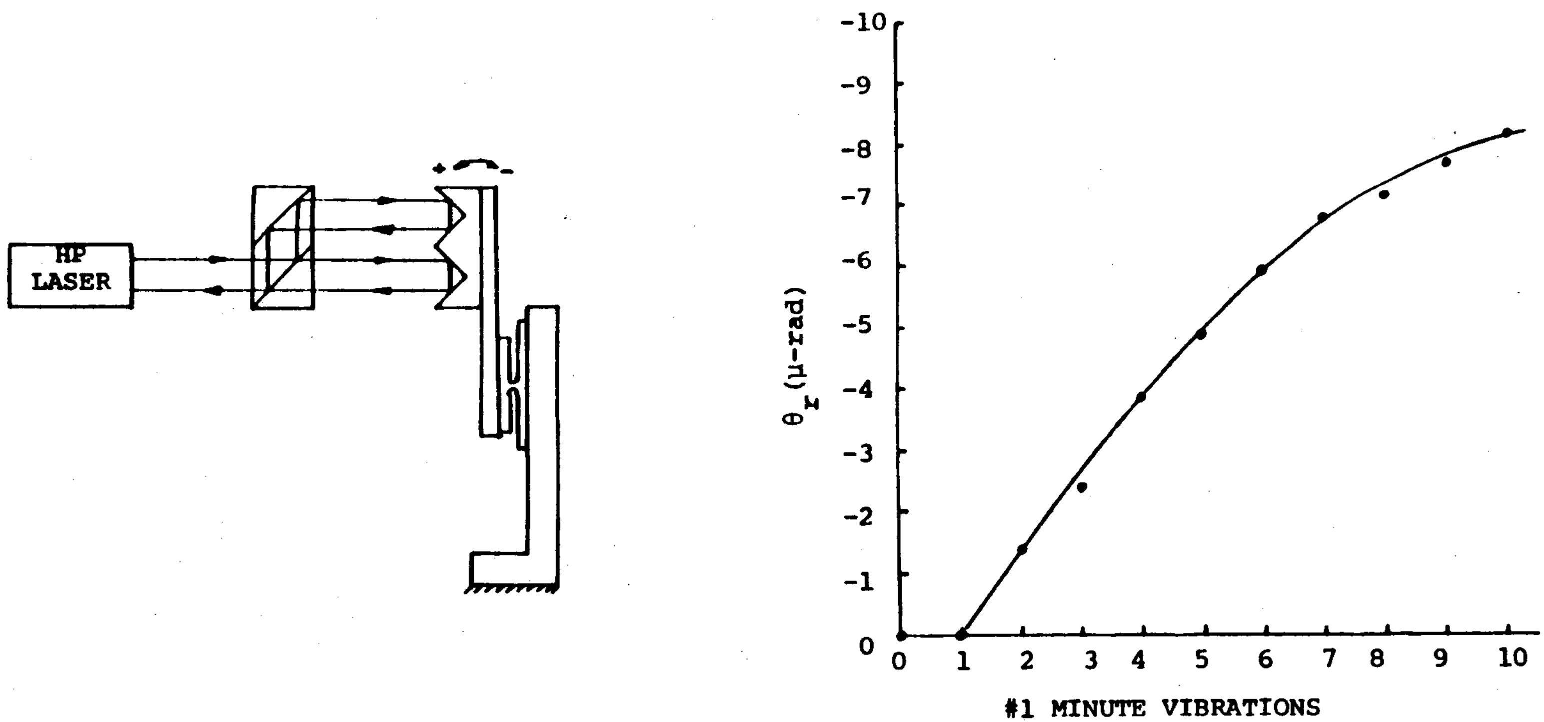


Figure 3.5-8. Acoustic Environment Within the Shuttle Paylcad Bay



- **After initial vibrational relaxation, the mirror mount was stable when vibrated for 3 minutes.**
- **Probably use static mirror mounts in flight system.**

Figure 3.5-9. Preliminary Vibration Test of Mirror Mount

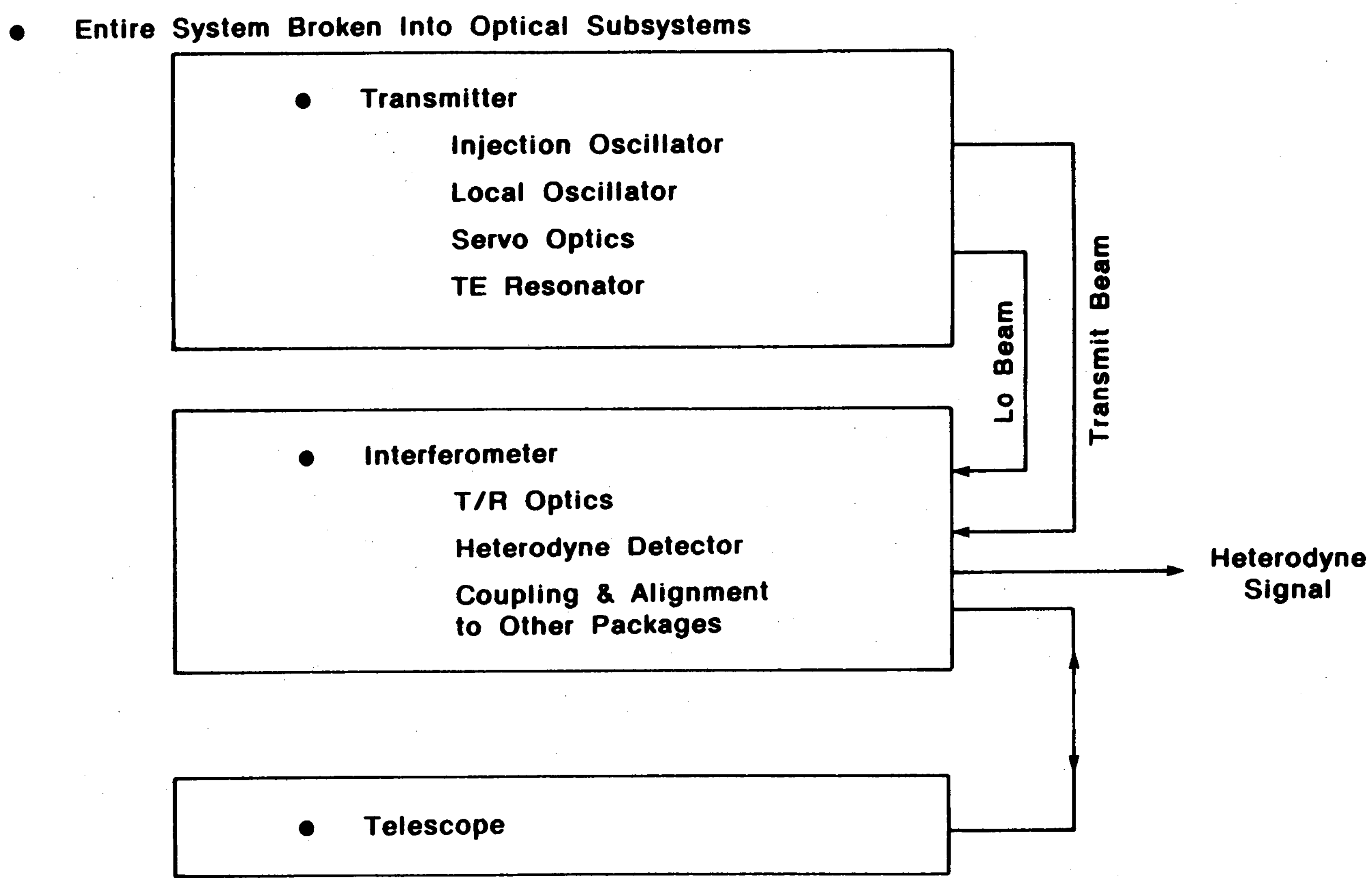


Figure 3.5-10. Optical Alignment Considerations

physical embodiment of this objective is discussed further below. The critical alignment point is the transmitter TE resonator, which has stringent requirements and large physical size.

Figure 3.5-11 depicts the division of alignment functions. The transmitter bench and its components deliver high quality beams to the interferometer bench. The interferometer bench provides the alignment function between the transmitter beams and the telescope input/output beams. The error budget for the transmitter alignment is given in Table 3.5-1.

3.5.3 Active Alignment Approach and Procedure

The actively aligned elements of the transmitter use the injection and local oscillator beams as sources. Quadrant pyrolytic detectors placed at critical nodes require AM modulation of the cw lasers. Beams are sampled by permanent beam splitters. A small number of alignable optics will be required. Mounts will be actuated by magnetic, thermal, hydraulic, mechanical, or piezoelectric methods. During initial alignment, a large number of misalignments must be dealt with. This will be time consuming and will require a multiparameter search procedure before the lidar can be actuated. This process uses little power. On-station alignment will be continuous, closed loop, and low bandwidth. Finally, the optical alignment sensitivity can be reduced through optical design measures, such as overfilling the servo detectors to reduce overlap sensitivity. The transmitter active alignment components are listed in Table 3.5-2.

3.5.3 Criticalities

Criticality of the optical eqiupment to the design environment is given in Table 3.5-3.

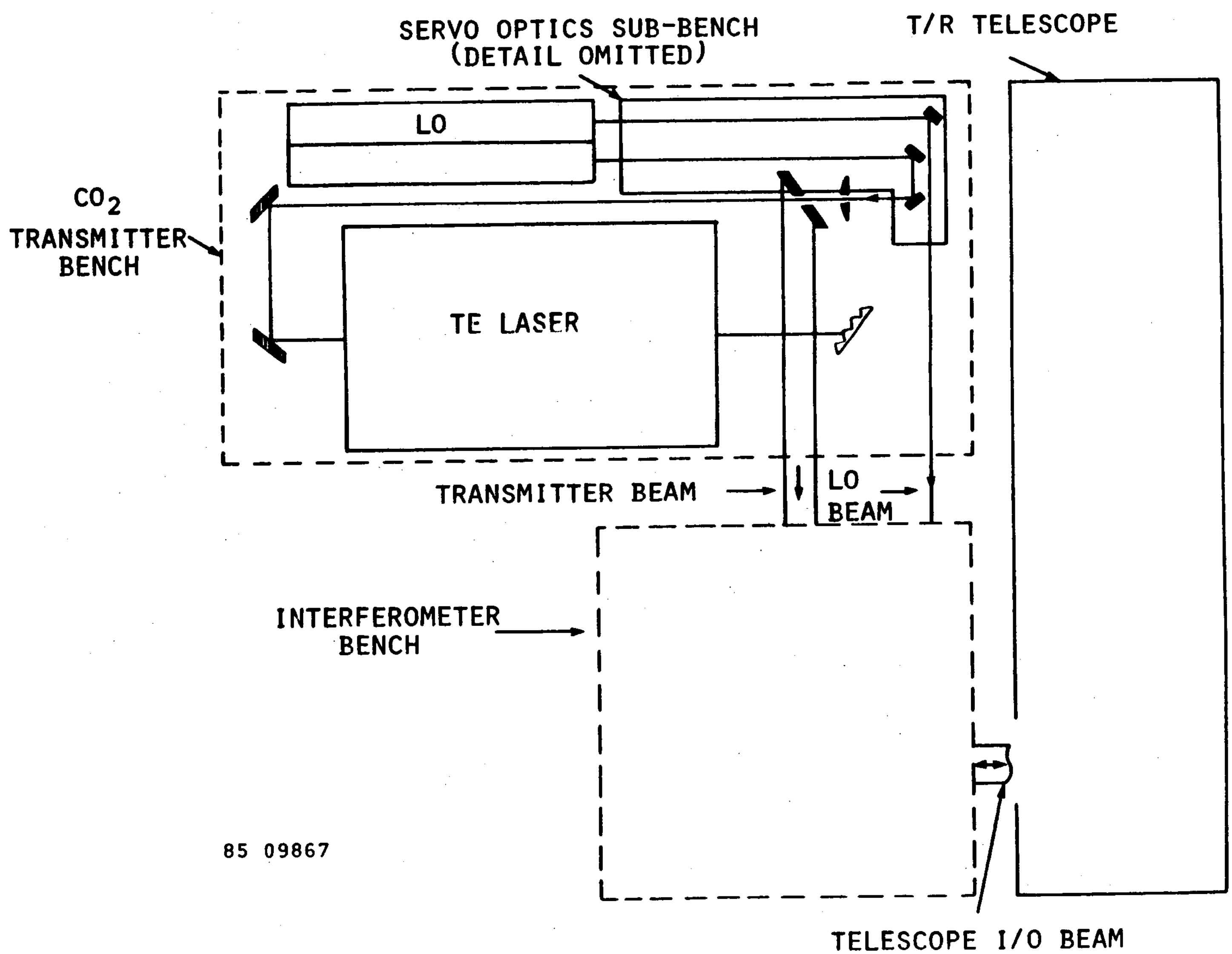


Figure 3.5-11. Division of Alignment Function

Table 3.5-1

PRELIMINARY TRANSMITTER ALIGNMENT BUDGET

Subunit	**Solid-Body Motion of Subunit With Respect to Transmitter Bench**	**Single-Optic Motion With Respect To Subunit**
Injection Oscillator	0.3 mrad	$\leq$ 1 mrad
Local Oscillator	0.3 mrad	$\leq$ 1 mrad
Servo Sub-Bench	0.3 mrad	100 μrad
TE Resonator Optics	NA	50 μrad
TE Laser Head	1 mm transverse	10 mrad

Table 3.5-2

TRANSMITTER ACTIVE ALIGNMENT HARDWARE REQUIREMENTS

IO, LO	None
Servo Sub-Bench	4 quadrant detectors 12 actuators
TE Resonator	2 quadrant detectors 4 actuators

Table 3.5-3

CRITICALITY OF EQUIPMENT TO DESIGN ENVIRONMENT

SUBSYSTEM: Optical/Structural ITEM	THERMAL VACUUM	THERMAL CYCLE	SINE VIBRATION	RANDOM VIBRATION	ACOUSTIC NOISE	PYROSHOCK	ACCELERATION	HUMIDITY	PRESSURE	LEAKAGE	CHEMICAL CORROSION	SHOCK VIBRATION	FLOW	HIGH VOLTAGE	EMP
Optical Table		o	o	o	o	o	o					o			
Cavity Space Frame		o	o	o	o	o	o					o			
Infrared Detectors														o	o
Oscillators		o	o			o						o			
Servo Sub-Bench			o	o	o										
TE Laser Resonator			o	o								o		o	
Acoustic Shell	o		o	o	o		o								o

3.5.4 Risk Assessment

The component risk assessment is presented in Table 3.5-4. It is anticipated that a design verification test will be required to substantiate the maximally passive design goal.

3.6 CONTROL AND DATA SUBSYSTEMS

3.6.1 WINDVAN Control Configuration

The WINDVAN transmitter is controlled by a standard commercial-grade microcomputer (DEC LSI-11/23). This processor performs automated system startup and shutdown housekeeping functions. During normal operation, a wide variety of error detection and recovery functions are active. All normal operator functions are performed via a touch-screen CRT terminal, using a multimenu "soft pushbutton" approach.

Other than the touch screen, the only other operator contact required for normal operation is turning on of circuit breakers, when starting from a cold condition, and alignment of optics using manual mount controls.

Storage of the operating program and system configuration information is on a small Winchester disk. Interface to the transmitter hardware is via a single parallel port interfaced to the microprocessor bus (Q-bus). Serial RS232 ports on the bus are used for the operator terminal, and for command input and status output to a master lidar processor.

3.6.2 SCALE Control Configuration, Requirements, and Criticality

The proposed SCALE configuration is much the same. A single modest local processor is adequate to handle all transmitter housekeeping and monitoring functions. As described in Section 3.5, autoalignment functions must be added to the set of control functions currently implemented in WINDVAN. Low bandwidth bidirectional communications, either to the ground

Table 3.5-4

OPTICAL/STRUCTURAL COMPONENT RISK ASSESSMENT

NATURE OF DEVELOPMENT		SUPPORTING ANALYSIS/DATA		FUNCTIONAL CRITICALITY		TOTAL
ITEM OPTICAL TABLE	VALUE		VALUE		VALUE	
CATEGORY 3	4	CATEGORY 3	2	CATEGORY 1	3	24
ITEM CAVITY SPACE FRAME						
CATEGORY 3	4	3	2	1	3	24
ITEM IR DETECTORS						
CATEGORY 4	2	4	1	1	3	6
ITEM OSCILLATORS						
CATEGORY 4	3	4	1	1	3	6
ITEM SERVO SUB-BENCH						
CATEGORY 4	2	4	1	1	3	6
ITEM TE RESONATOR OPTICS						
CATEGORY 4	2	4	1	1	3	6
ITEM						
CATEGORY						

or to a mission-specialist operating panel, will allow remote operation and status monitoring. Remote operation of prime power and coolant shutoffs is envisioned to be performed by the mission specialist. These requirements are summarized in Table 3.6-1.

Table 3.6-2 summarizes the criticality of data-related components in the standard format of this report. The control components are essential to successful transmitter operation and, hence, must be engineered for maximum reliability in the STS environment.

3.6.3 Risk Assessment

Table 3.6-3 summarizes the component level risk assessment in the format used throughout this report. The technology associated with the data and control functions is extremely well developed, but also critical to the mission. The overall risk associated with these elements of the transmitter design remains low because of the excellent engineering database available, both for the control requirements and for the technology necessary to implement those controls.

Table 3.6-1

CONTROL AND DATA REQUIREMENTS FOR SPACE SHUTTLE LIDAR TRANSMITTER

- o Local Transmitter Controller ≈ 0.1 MIPS
  - Autoalignment
  - Laser system startup, sequencing, shutdown
  - Servo autolock and monitor
  - Fault detection and protection
- o Downlink Data Rate ≈ 2400 bps
  - Transmitter status
- o Uplink Data Rate ≈ 300 bps
  - Transmitter command
  - Parallel mission specialist command?

Table 3.6-2

CRITICALITY OF EQUIPMENT TO DESIGN ENVIRONMENTS

SUBSYSTEM:

ITEM	DESIGN ENVIRONMENTS: THERMAL VACUUM	THERMAL CYCLE	SINE VIBRATION	RANDOM VIBRATION	ACOUSTIC NOISE	PYROSHOCK	ACCELERATION	HUMIDITY	PRESSURE	LEAKAGE	CHEMICAL CORROSION	SHOCK VIBRATION	FLOW	HIGH VOLTAGE	EMP
Telemetry Interface	o	o	o	o		o	o								o
Supervisory Computer	o	o	o	o		o	o								o
Sensor and Control Electronics	o	o	o	o		o	o								o

Table 3.6-3

DATA AND CONTROL COMPONENT RISK ASSESSMENT

NATURE OF DEVELOPMENT		SUPPORTING ANALYSIS/DATA		FUNCTIONAL CRITICALITY		TOTAL
ITEM TELEMETRY INTERRACES	VALUE		VALUE		VALUE	
CATEGORY 4	2	CATEGORY 4	1	CATEGORY 1	3	6
ITEM SUPERVISORY COMPUTER						
CATEGORY 4	2	4	1	1	3	6
ITEM SENSOR AND CONTROL ELECTRONICS						
CATEGORY 4	2	4	1	1	3	6
ITEM						
CATEGORY						
ITEM						
CATEGORY						
ITEM						
CATEGORY						
ITEM						
CATEGORY						

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Section 4

TRANSMITTER DEVELOPMENT PLAN

4.1 OVERVIEW

We divide development into Conceptual Design (Phase A), Preliminary Design (Phase B), and Detailed Design and Development Phases (Phase C/D). Figure 4-1 shows the logical relationship of the activities within these various phases.

No major technology development is required for the transmitter concept presented in this report, but the need for additional testing of certain critical components is anticipated. We believe that these tests are most appropriate during Phase B, or perhaps even earlier. These tests will completely resolve all remaining uncertainty concerning the capability of WINDVAN technology to meet SCALE requirements. After these tests have been completed, development of the SCALE transmitter can proceed along a well defined path using established space hardware methodology.

Details of the recommended development activities are described in Section 4.2. Because of the importance of the qualification testing to determination of both program costs and risk, the test plan is described separately in Section 4.3. In Section 4.4 we develop a cost estimate of the complete development cost of a flightworthy transmitter, through delivery to KSC for shuttle integration. Section 4.5 is a summary of STI's conclusions and recommendations concerning development of a SCALE transmitter based on WINDVAN technology.

4.2 DETAILED DEVELOPMENT PLAN

Figure 4-2 shows the schedule for the suggested program. The goals of each phase are described below. Total elapsed time for development of the transmitter is estimated to be 56 months, from start through delivery

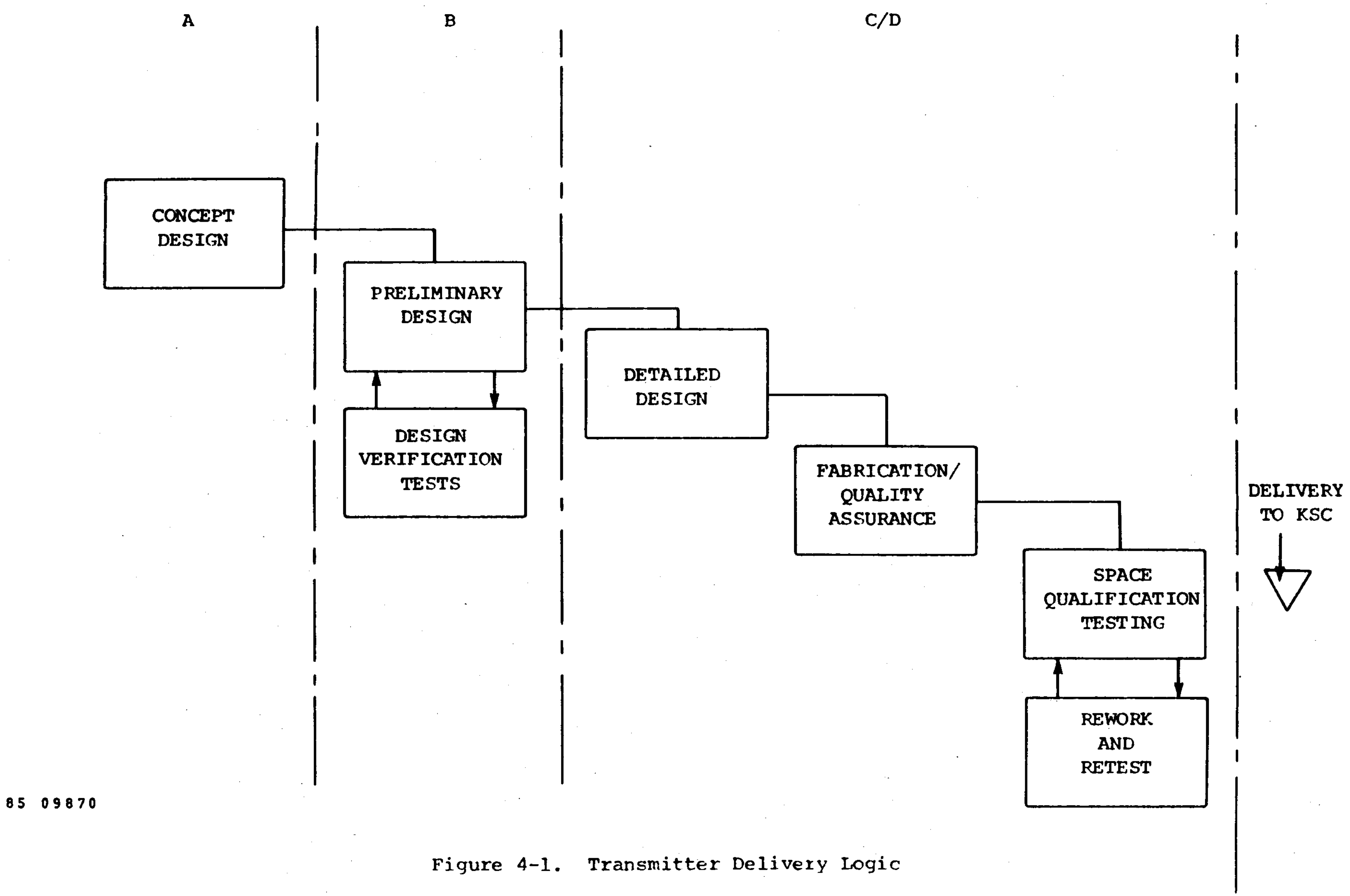

Figure 4-1. Transmitter Delivery Logic

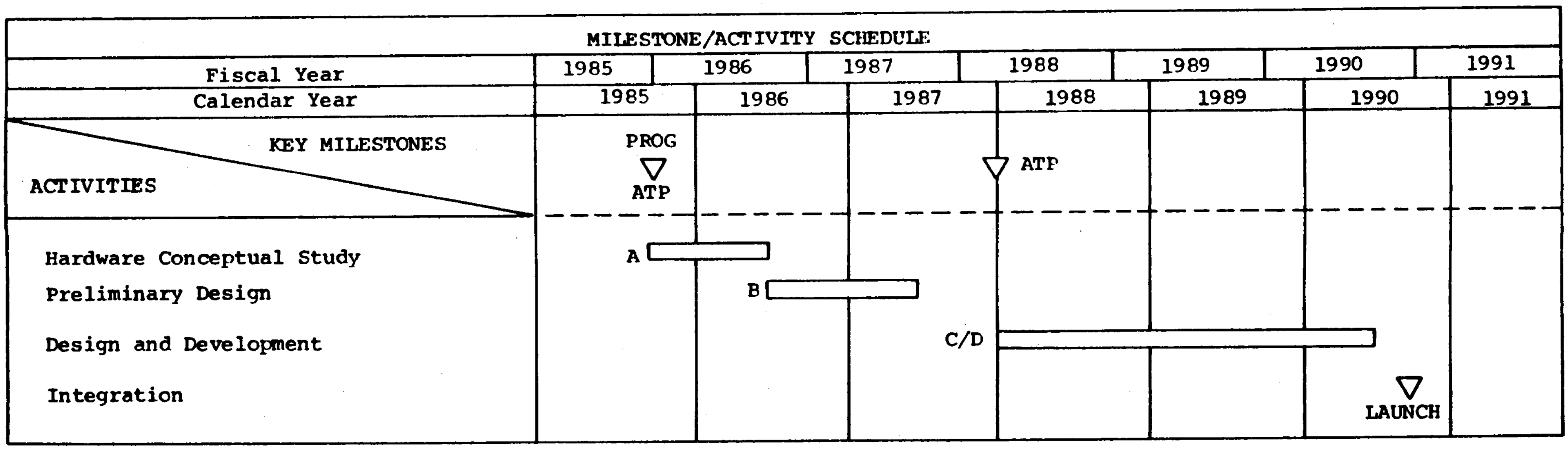

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Figure 4-2. Program Schedule

to KSC. The schedule shown includes a slightly longer total elapsed time because of interfaces with the NASA decision making process.

Phase A

The hardware conceptual design phase leads to a final definition of the transmitter approach. Technology selection and rough configurations for all transmitter subsystems will result from this study. Any transmitter components requiring further development or testing and any areas of special risk will be identified during this phase. A complete description of the projected transmitter performance also will be developed.

Phase B

Phase B will result in complete definition of the transmitter configuration. System layouts, preliminary interface definition documents, and identification of component level requirements are the primary outputs of Phase B.

Component performance requirements will be compared with the state of the art. In those areas where there is insufficient design data to make this comparison, or if there is a concern as to component adequacy, special tests will be designed to validate the required performance levels. Table 4-1 lists the series of such tests that we currently envision to be required.

Using the existing technology database, augmented by the results of the proposed design verification tests, Phase B should result in elimination of all uncertainties concerning the technical feasibility of the SCALE transmitter approach.

Table 4-1

TRANSMITTER DESIGN VERIFICATION TESTS

Component	Issue	Test Description
Modulator	Solid-state Switch Performance	Breadboard Modulator Dummy Load
Optical Bench Structural Supports	Passive Alignment	TBD
Gas Utilization**	Catalyst Performance Operating Temperature	Breadboard Regeneration Flow Loop
Preionizer	Corona Bar Life	Breadboard pulsed CO_2 laser*

* e.g., STI 20 W CDL laser

** Not required, if gas rejection acceptable; not currently costed

Phase C\D

Phase C\D begins with detailed engineering design of the complete transmitter subsystem, including STS and SCALE interfaces, support hardware, and any special tooling required. After design completion and review, procurement and fabrication begins, leading to full transmitter system assembly and functional checkout. To ensure appropriate costing, the necessary design documentation and quality assurance appropriate to a flight-qualified device have been explicitly identified.

Qualification testing is described in detail in Section 4.3. The final Phase C\D task consists of rework and retest to correct deficiencies uncovered during qualification testing.

4.3 QUALIFICATION TEST PLAN

We envision that six distinct types of testing will be required to qualify the SCALE transmitter system. These are (1) mechanical mode analysis, (2) vacuum-thermal exposure, (3) EMI generation, (4) static mechanical loading, (5) acoustic loading, and (6) life testing. These tests will be applied, as appropriate, to individual transmitter subsystems and then to the full transmitter system as a unit. The full system test series is proposed to occur twice. The second full system test will validate the success of any rework required to correct deficiencies. Table 4-2 shows in matrix form which tests will be applied to which transmitter subsystems.

4.4 ESTIMATED DEVELOPMENT COST

We have estimated the cost of development of a SCALE transmitter from conceptual design through delivery to KSC in flight-ready condition. These costs are summarized in Table 4-3. The basis for these estimates follows.

COMPONENT \ TEST	Modal Analysis	Vacuum Thermal	Electromagnetic Interference	Static Loading	Acoustic Vibration	Life
Laser Head	O			O	O	O
Modulator	O		O	O	O	O
Optical Bench/ Optics	O			O	O	O
Data Handling & Control Electronics			O			O
Assembly	O	O	O	O	O	O

Table 4-2. Transmitter Space Qualification Tests

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Phase A costs are projected from the effort involved in the conceptualization of the WINDVAN design and from the effort invested in this study.

Phase B costs are dominated by the DVT effort, which has been estimated by comparison with similar STI technology programs. The remaining design cost is based on the WINDVAN experience, scaled by a complexity factor to account for space-related design issues.

In Phase C/D, a number of cost rationals are used. Detailed design is based on the WINDVAN experience, with an overall factor applied for the more complex space-qualified design. In addition, a documentation cost for STS interface specification, test planning, installation and operation manuals, and safety and qualification assurance has been included. Fabrication and checkout costs are based on WINDVAN experience. Quality assurance costs for compliance with space requirements have been assigned at the level of ≈15% of fabrication costs.

Testing has been costed using the test plan described in the previous section. Pricing on a per-test basis is assigned using values obtained from an active aerospace testing vendor (generous assistance of Ball Aerospace Division is gratefully acknowledged).

Rework has been assigned a cost equal to 25% of initial fabrication. Retesting has been costed using the same per-test costs as previously described.

4.5 CONCLUSIONS AND RECOMMENDATIONS

We conclude that a SCALE transmitter using the basic WINDVAN design approach is feasible. Development of new technology is not required. Appreciable engineering redesign will be required for repackaging the WINDVAN design for shuttle compatability. A more compact pulsed power layout has been proposed, and many design changes will be required for

vacuum compatability and for improved launch/landing survivability. In addition, some degree of remote optical alignment capability may be required.

The transmitter concept developed in this study provides performance equal in all respects to the NOAA/STI WINDVAN transmitter. The predicted prime power consumption, size, and weight of the transmitter are given in Table 4-4. Since full 50 Hz operation results in power consumption that exceeds MSFC goals, the power required for 25 Hz operation is also given in the table.

The only significant change of approach identified is the replacement of thyratron pulsed power switches with solid-state elements. The basic switching devices (RBDTs) proposed are well proven, but their use in a discharge pumped laser is not. As a result, tests to optimize matching of a solid-state switch to the laser load are recommended as part of the Phase B Design Verification Tests. Life testing of the solid-state devices under realistic laser loads also is recommended.

In summary, we can find no major technological barrier to successful development of a SCALE transmitter using WINDVAN design principles. The few remaining technology issues can be resolved by a set of relatively small Design Verification Tests, which can be completed very early in a SCALE development program. Since the proposed DVTs are not extremely design specific, it may be desirable to accelerate some or all of them. The engineering task which remains is substantial, but tractable. It should begin as early as possible to allow maximum reduction of risk in the resulting design.

During this study, the authors have come to believe that a SCALE mission in the early 1990s is an attainable goal. This optimism is a result of the study and was not a starting point. However, this goal can be met only with a strongly focused, concerted development program that begins as soon as possible.

Table 4-4

SUMMARY OF SCALE TRANSMITTER POWER, WEIGHT, AND VOLUME REQUIREMENTS

Subsystem	Power (W) @50Hz	Power (W) @25Hz	Weight (Kg)	Volume (cu m)
Laser (Mechanical)	75	75	225	0.219
Laser (Electrical)	2600	1300	455	0.250
Gas Supply			30	0.079
Thermal Management	315	315	68	0.140
Control, Command, Commn.	100	100	15	0.012
Optical/Structural	250	250	580	0.540
TOTALS	3490	2190	1388	1.161

For the near-term, we strongly recommend that NASA undertake conceptual design of the transmitter, at a relatively low level. We further suggest that consideration be given to acceleration of the needed technology verification tests into the FY86 time frame. These actions will result in considerably enhanced confidence in SCALE's success at a relatively modest cost.

APPROVAL

SHUTTLE COHERENT ATMOSPHERIC LIDAR
EXPERIMENT (SCALE)

By J. Bilbro, R. Beranek, D. Fitzjarrald, J. Mabry

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

W. C. Bradford
Director, Information and Electronic Systems Laboratory

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16. ABSTRACT

This document contains the results of a study to design and accommodate a simplified version of a Coherent Lidar System which is capable of performing tropospheric wind measurements from orbit. The document contains data on: system sensitivity, orbital analysis, science experiments, preliminary system design, accommodations, and a detailed look at the Space qualification of a 2J. CO_2 laser.

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